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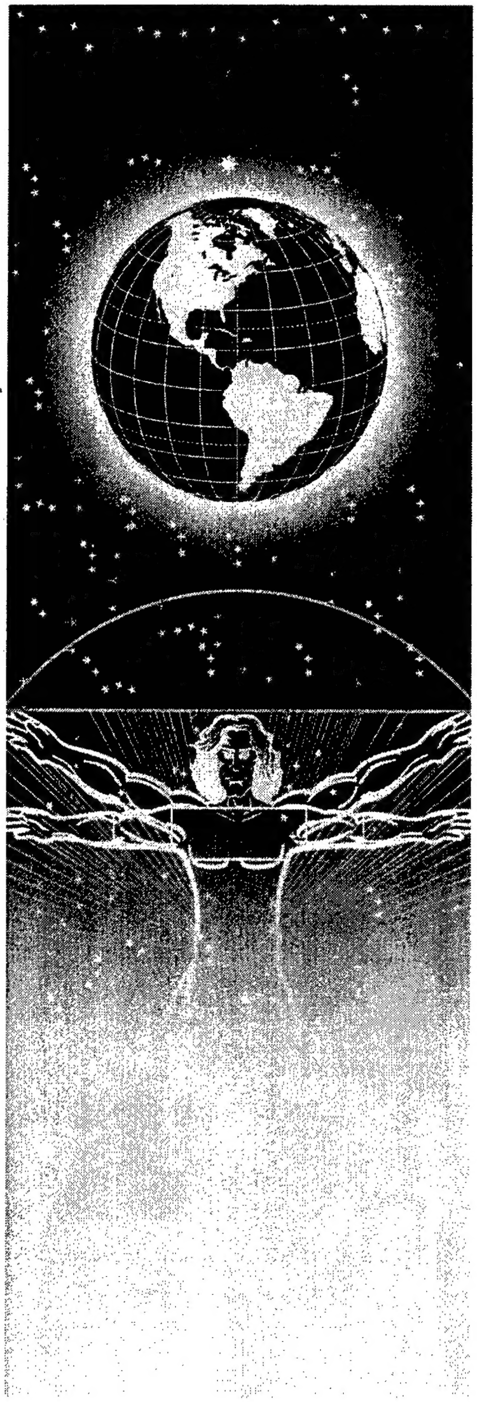

UNITED STATES AIR FORCE RESEARCH LABORATORY

AMBIENT LIGHT CONTROL USING GUEST HOST LIQUID-CRYSTAL DYE SYSTEMS

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FOR THE COMMANDER

MARIS M. VIKMANIS
Chief, Crew System Interface Division
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13. ABSTRACT *(Maximum 200 words)*

This program developed a technology for varying the transmittance of flight-helmet visors from 15-60% under electronic control. It is based on controlling the orientation of dichroic dye molecules, using liquid crystal. No polarizers are used, scattering is low, the color is neutral, the power requirement is low, and the failure mode is clear, i.e., the visor reverts to its maximally transmitting state when power is removed. Demonstration devices were produced on flat PET plastic substrates and toroidal polycarbonate visors of the type used with the HGU-55/P flight helmet. Technical details of the program, remaining problems, and plans for commercialization are discussed.

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Executive Summary

Increasing interest in helmet-mounted displays (HMDs) has fueled research in variable transmittance visors (VTVs) because a VTV can reduce glare and increase HMD contrast in bright lighting conditions. The ideal VTV will be an electrically controllable light valve that allows the pilot to adjust visor transmittance (tint) to the level appropriate to the ambient lighting conditions. Liquid-crystal based devices can provide an efficient method for accomplishing this. Because flight helmets utilize polycarbonate visors, VTVs must be implemented on complex curved, plastic substrates. Liquid crystal devices, however, are typically implemented on flat glass substrates. The goal of this proposal was to evaluate the feasibility of implementing liquid crystal technologies on curved plastic substrates. To achieve the desired requirements, AMI proposed use of a novel liquid crystal configuration, Variable Attenuation Liquid Crystal Device (VALiD). VALiD is a dichroic dye and liquid crystal based guest-host system. The specific configuration allowed for a fast system that fails to the clear state. Furthermore, the degree of polarization dependence could be tailored for use in different applications. Given the novel nature of the system, new dyes and mixtures had to be developed to meet the requirements for daytime usage. Since the dye and liquid crystal interact collaboratively, all components of the mixture had to be simultaneously optimized. The degree of performance was measured by the degree of the order of the dye with respect to the liquid crystal orientation. Higher degree of order results in a better alignment of the dye dipole and a subsequent improvement of the performance. Conventional dyes have been shown to have order parameters of 0.7-0.8 (theoretical maximum is 1). Since the performance is highly nonlinear with respect to this parameter, it was thought that there was a barrier from achieving order parameters higher than 0.82. However, AMI embarked and developed new materials and was able to identify a new class of dyes which along with its mixture produce order parameters of 0.85. Currently AMI has highest order parameter dyes recorded across the visible spectrum. This has resulted in high performance and a window swing of ~50%.

During the funding period, AMI was able to implement VALiD on thin, flexible, flat plastic substrates. This system was extended from thin flexible plastic to doubly curved polycarbonate substrates and a prototype was fabricated using two semi-conformal visors as base substrates. The thickness of the substrates used resulted in reduction of lifetime and durability. In addition, undesired reflections from the ITO and liquid crystal layers, as well as the external surface of the visor reduced applicability for HMD systems. AMI, then, researched methods for minimizing the double reflections and parallax associated with using thick visors as substrates. An AR coating configuration was developed and used for the interior surfaces of the visor pairs. While an improvement was observed, it was determined that in the total dark conditions, the reduction of the secondary reflections was not sufficient for HMD applications. Given this AMI embarked on a novel path of using a thermoformed cell for VTV applications. Preliminary results have indicated that such a system will have the potential to overcome the issues encountered. AMI is currently the only company that has been able to reduce a LC technology on doubly curved plastic substrates.

In addition to the technology development, AMI placed a significant effort in commercialization of its technology for consumer market applications. These include, sunglasses, ophthalmic glasses, ski goggles and motorcycle helmets. It is currently in midst of discussions with potential strategic partners for mass product commercialization.

1. INTRODUCTION

1.1 Variable Transmittance Visor requirements

Helmet-mounted displays (HMDs) superimpose visual information on the pilot's panoramic view of his/her surroundings. The information must be legible to the pilot regardless of the intensity of ambient light, which may vary from direct sunlight to near total darkness. To provide an adequate contrast ratio, essential for reliable perception, either the intensity of the projected image carrying the information or of the ambient light reaching the pilot must be controllable. It can be difficult to produce sufficient display luminance under bright viewing conditions, so the more elegant approach is to adjust see-through transmittance. Ideally, this adjustment should occur automatically as the lighting conditions change; there should also be a manual adjustment that allows the pilot to tailor the system to his/her preference. The device needs the following characteristics: it should

i. have adjustable attenuation controllable by the operator
ii. be colorimetrically neutral across the visible spectrum
iii. have response time comparable to that of the human iris (<1 s)
iv. transmit a clear image (no haze) at all levels of attenuation
v. fail to the clear state, i.e., the visor must become transparent, rather than dark, if the device fails
vi. be compatible with conventional plastic helmet visors
vii. have low power consumption
viii. be UV resistant
ix. show low thermal sensitivity.

A number of technologies have been evaluated for this purpose without success. These included photochromic dyes, electrochromic systems, and suspended particle dispersion.

Photochromic material has wide use in commercial prescription eyewear. These materials change when exposed to UV radiation. The darkening properties of simple photochromic materials cannot be controlled by an operator, which makes them unsuitable for this application.

Electrochromic systems are currently in use for Auto-dimming applications. These systems use a chemical reaction (RedOx) to alter the chemical state of a dye. The dye, in its oxidized state absorbs visible light. The system works on a bipolar electrical connection with DC current. While applicable for some applications, this system is highly dependent on the electrical pathways. As such, it is difficult to produce the system on flexible substrates. In addition, the current driven aspect of the technology results in "irising" in the on-state which has a detrimental effect on the visual acuity of the visor. The speed of change is highly dependent on the substrate size and transparent coating thickness. For usable range, this results in a few seconds which is not suitable for application stated. Finally, the system is inherently bistable. To achieve fail-safe configuration, the system has to be shorted. The RC constant of the system will then dictate the relaxation time which can be of several seconds to minutes.

Suspended particle dispersion offers a fast mechanism for light control. However, the system is inherently scattering with high haze and as such unusable for eyewear applications.

Because of their unique optical properties, liquid crystals offer the possibility of low cost, lightweight methods for efficient light control. Conventional liquid crystal technologies offer means of achieving

these goals. However, they are implemented on glass substrates. To date, there has been no commercial liquid crystal device on curved plastic substrates.

Table 1 summarizes the different possible controllable technologies applicable with their characteristics. It can be seen that the LC devices has the best chance of achieving all desired requirements for a VTV

Table 1: Characteristics of active technologies for VTV applications

Features	LC devices	Electrochromic	SPD
Normal State	Clear	Clear or Dark	Dark
Fail-Safe	Yes	No	No
Polarization	Yes	No	No
Window	50%	50%	40%
Haze	0%	0%	15%
Switching	Voltage	Current	Voltage
Speed	ms to seconds	seconds	ms to seconds
Color	Any	Grey & Blue	Black & Blue
Plastic	Yes	Yes	Yes
Curved	Yes	Yes	Yes
Flexible	Yes	No	No

Given the above, AMI decided to explore the possibility of using liquid crystals for VTV applications. This required a novel approach on the LC configuration as well as processing.

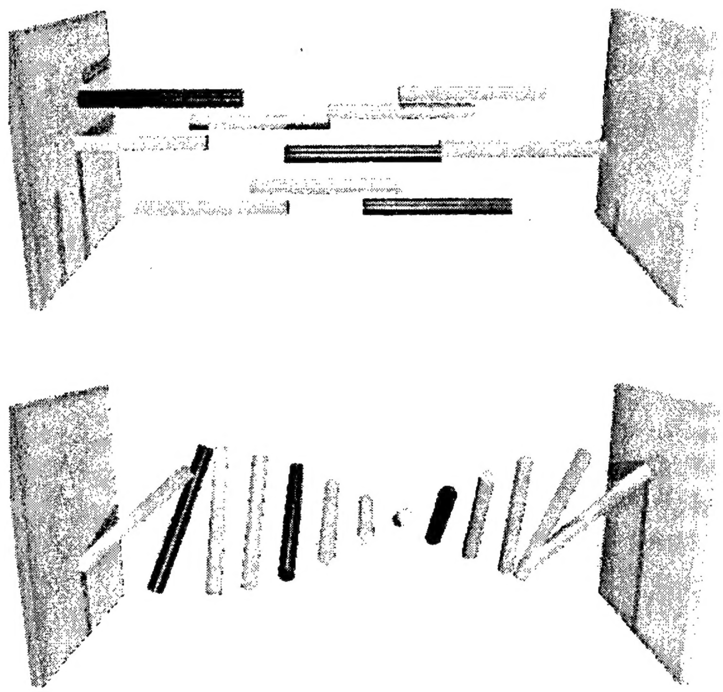
1.2 Guest-Host system configuration

For optical applications, it was necessary to determine a method for fabricating LC devices in which the dark state transmission was not below 15% and conversely achieving a >60% transmission in the clear state. This is opposite of the expected norm for these devices. In particular, in LCDs the dark state is more important that the clear state. This is to insure a good "black" state as well as viewing angle. The clear state transmission is sacrificed to be ~30%. The viewing angle associated with a cross polarized technology also limits their use to flat systems. There are some welding helmets which use the cross polarized geometry for achieving a good extinction. However, these systems are not suitable for VTV applications.

Starting with the VTV requirement, it is clear that it is necessary to develop a novel system specifically designed for this application. As such, we considered a number of different LC configurations and evaluated their physical range of capabilities for VTV application. Based on these findings, we developed and demonstrated a Variable Attenuation Liquid Crystal Device (VALiD) consisting of a dichroic dye (DD) dissolved in a liquid crystalline host material. The system addresses and meets the requirements presented above. We modeled and prototyped several cells using a fails-clear geometry version of the configuration. The device shows a fast, colorimetrically neutral, clear response across the visible spectrum. Further, we demonstrated the technology is compatible with using plastic substrates. Finally, we have been successful at implementing it as a Variable Transmittance Visor (VTV) on doubly curved polycarbonate visors.

Design of the system configuration for the Variable Attenuation Liquid crystal Device (*VALiD)* was based on the requirements presented above. Conventional liquid crystal devices utilize the birefringence properties of the host sandwiched between two polarizers. As stated earlier, these systems are not suitable for HMDs due to shortcomings in using polarizers, such as clear-state transmission and viewing angle dependence. A proper geometry of a dichroic-dye liquid-crystal guest-host system does not exhibit these shortcomings. In dichroic dyes, the absorption cross-section depends on the relative orientation of the dye to the incident field polarization. By use of a liquid crystal host to align the dye, this dependence can allow electronically controlled light transmittance. In particular, by changing the orientation of the liquid crystal, the orientation of the dye and, hence, the absorption and attenuation of light can be controlled. Without the use of polarizers, changes in the transmittance are primarily due to the dye since liquid crystal is transparent in the visible region of the spectrum. Given this, the system can be designed to have a high clear-state transmission and little viewing angle dependence. Furthermore, suitable combinations can be formulated to yield a colorimetrically neutral system. The switching speed for such a system is dictated by the response of the liquid crystal, which is in millisecond regime and therefore much faster than the required response. To maintain clarity at all levels of attenuation, it is necessary to minimize light scattering. This requirement suggests the system cannot be constructed using SPD, PDLC- or NCAP-based devices, which exhibit haze in all transmission states. Conventional liquid crystal devices can be made to satisfy these conditions. However, they have not been, till now, compatible with plastic substrates. In addition, the severe curvature of the helmet-visor substrates would make conventional processing impossible. The issue of compatibility with curved plastic substrates is addressed in subsequent sections.

Figure 1 shows the final geometry that was used to achieve the performance needed. The system uses a homeotropic surface treatment and a negative dielectric material. This is opposite of the conventional LCD products which uses a homogenous surface treatment and a positive dielectric LC host.



(a)

(b)

Figure 1. Geometry for FC-VALiD in (a) unpowered, (b) powered states. Application of voltage results in orientation of LC perpendicular to the surface normal. Note that the LC can exhibit a twist in the powered state.

In principle, it is possible to design a configuration that is non-absorbing in the unpowered state and returns to this configuration in the event of power loss. The orientation of the liquid crystal, and therefore the guest dye, depends on the magnitude of the applied voltage, enabling continuously variable attenuation. Polarization dependence of the transmittance can be controlled by using a twisted liquid crystal configuration. The ratio of the pitch of the twist to the wavelength of light determines the extent to which the system response is polarization dependent. Stress relaxation in liquid crystals typically results in little or no haze. While this geometry has been suggested for display applications, its use for continuous varying eyewear is hindered by the development of scattering textures.

To obtain a fails-clear configuration, it is necessary for the dye absorption to be minimal in the relaxed state. This can be achieved by either the use of (i) liquid crystal with positive dielectric anisotropy and a negative dichroic dye or (ii) liquid crystal with negative dielectric anisotropy and a positive dichroic dye. The surface alignment needed for the first option is planar; the second option requires homeotropic alignment. We have found that greater transmittance in the clear state can be obtained if we use the latter geometry. The system presented was named Fail-to-Clear VALiD (FC-VALiD).

Several cells were fabricated based on the above configuration. The cells were made using flat glass substrates. ITO coated substrates were coated with a homeotropic alignment layer and cured at 200° C. They were then assembled with 5-micron spacers and filled a variety of liquid crystal mixtures. The performance of the system was tested for a variety of commercial dyes and chiral concentrations. It was

determined that the system would be applicable to this application and as such was used as the base configuration for VALiD.

Figure 2 shows the wavelength dependence of the transmission in the powered and unpowered states for the FC-VALiD configuration. It can be seen that the transmission decreases with voltage and the absorption spectrum can be made colorimetrically neutral.

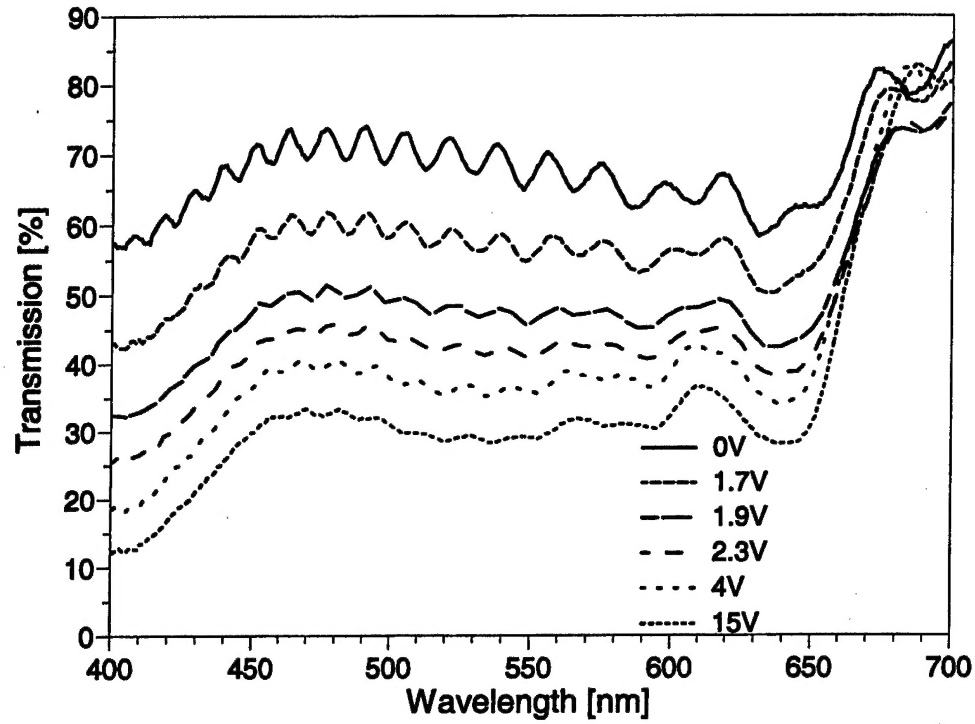


Figure 2. Wavelength dependence of the transmission of FC-VALiD. Note that the transmission is greater in the unpowered state and the device is colorimetrically neutral.

This configuration demonstrated that our system was viable in achieving the desired effect. However, these preliminary results had to be extended to achieve a VTV. This required investigation of all aspects of this configuration as well as demonstration that the configuration could be implemented on curved plastic substrates.

The goal of the project was then to optimize this configuration and implement the system on doubly curved plastic substrates. The results were then to be used to construct a VTV for evaluation by the Air Force.

2. RESEARCH EFFORTS

To achieve the requirements for a VTV it was necessary to categorize the efforts into (i) electro-optics and modeling, (ii) material synthesis and formulation and (iii) process development and prototyping. During the contract, AMI placed effort in all three categories to achieve the desired results.

2.1. Electro-optics

To date, the use of LC devices has been limited to displays and shutter applications. In these devices, the usage of the LC is to control the transmittance of the light as a valve. Restrictions placed on these devices in terms of the requirements for eyewear applications such as haze or clear state transmission were not placed for LCD and valve applications. On the contrary the conventional LC devices were fabricated to achieve the opposite characteristics required for VTV. In particular, the table below demonstrates some key feature requirements for LC based VTV and its contrast to conventional display applications needs.

Table 2: List of the electro-optic characteristic for LCD and VTV

	Displays	VTV
Dark state	~0%	>15%
Clear state	~25%	>60%
Haze	10-30%	<2%
Speed	10ms	100ms

To achieve the electro-optic responses required from the LC mixtures, the materials and their electro-optic responses were evaluated for VTV applications. Several cells were fabricated and filled with a variety of guest-host mixtures. The cell performance were used as a basis for evaluation of the VALiD configuration and then used in conjunction with theoretical modeling of light propagation and electro-optic response of the configuration for subsequent development of new materials and drivers.

In the first stage of the work, we performed computer modeling of a variety of possible LC/DD configurations. This included the LC director configuration and the optical properties associated with a given configuration. The results were used as a premise for fabrication of test cells and as a basis for selecting the initial candidates of the LC hosts and dyes.

2.1.1 Director relaxation model

The preferred orientation of liquid crystals is characterized by a "director" direction, **n**. This direction depends on the boundary conditions (anchoring at the substrate), natural tendency of the material (chirality) and imposed external fields. To determine the director configuration, the Helmholtz Free Energy of the system is minimized. For a distorted nematic, this is given by:

$$F = \frac{1}{2}K_1(\nabla\vec{n})^2 + \frac{1}{2}K_2(\vec{n}(\nabla\times\vec{n}))^2 + \frac{1}{2}K_3(\vec{n}\times(\nabla\times\vec{n}))^2 + K_2 q_0 \vec{n}(\nabla\times\vec{n}) + \frac{1}{2}\vec{D}\vec{E}$$

where K_1, K_2, K_3 are the elastic constants associated with splay, twist and bend deformations, q_o is the natural pitch of the nematic case when chiral dopants are present in the mixture, and D, E are the displacement and the electric field vectors. For simplicity we assumed that the director varies in one direction only, that is **n**=(n_x(z), n_y(z), n_z(z)). Minimization of the above free energy integrated over the sample is performed using variational calculus to obtain a solution for **n**(z). Since the equations for the director components are generally a series of coupled nonlinear differential equations, solutions are sought by a numerical method known as the director relaxation technique.

The dynamical equation for the director components (i=1,2,3) can be written as

$$\gamma\left(\frac{d\vec{n}}{dt}\right)_i = \delta F_i = \frac{\partial F}{\partial n_n} - \frac{d}{dz}\left(\frac{\partial F}{\partial(\partial n_i/\partial z)}\right)$$

where γ is the viscosity coefficient. At equilibrium, *dn/dt = 0*, this equation is known as the Euler-Lagrange equation. The equilibrium director configuration is obtained by converting the dynamic equations to a series of finite differential equations. The system is then allowed to evolve from a given initial condition to its final state.

2.1.2. Optics of stratified anisotropic media

In general, analytical solutions to Maxwell's equation in uniaxial crystals with arbitrarily varying optical axis are not possible. They can be solved for certain special cases such as a pure twist at normal incidence. Numerical methods, the most common of which is Berreman's 4x4 matrix method, can be used to give approximate solutions. Figure 3 shows the schematic for this approach. The sample is treated as a series optically thin, homogenous, birefringent slabs. Due to double refraction and the reflection on the interface between adjacent slabs, the Eigenmodes of propagation in each slab will be two forward propagating (ordinary and extraordinary like), and two backward propagating waves. For each slice, a differential propagation matrix, $D_i(\phi,\theta)$ can be obtained which relates the field in the i to that of the i+1 slice. The problem, then, reduces to a series of matrix multiplication giving a transfer matrix for the material. This is combined with the imposed boundary conditions to obtain the reflected and transmitted components of an incident field.

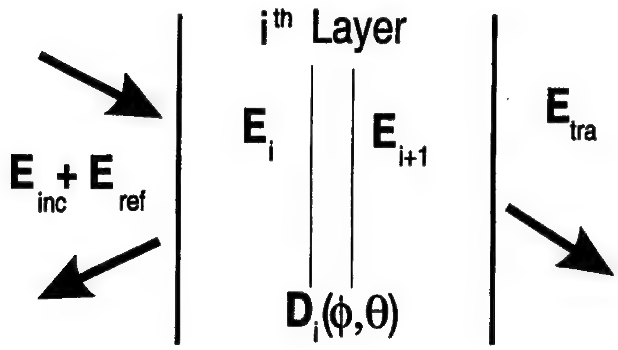


Figure 3. Schematic for matrix method approach. E_{inc}= incident, E_{ref}= reflected, and E_{tra}= transmitted fields.

This method can be extended to include absorption by a dichroic dye (DD) within the LC layer. In this case, complex refractive indices are used to characterize the nematic state:

$$n^{*}_{e,o} = n_{e,o} - i\frac{\lambda}{4\pi}\alpha_{e,o}$$

In the above equation n_e, n_o, α_e and α_o are the principal refractive indices and absorption coefficients of the guest-host system. The effect of absorption on the real part of the refractive index is negligible even in the case of the highest practical dye concentrations. Consequently, the n_e, n_o of the guest-host mixture are assumed to be equal to those of the pure host.

2.1.5. Simulations

A computer program was written to calculate the director configuration and the optical propagation through a LC cell. Several geometries were considered in an attempt to determine the optimum configuration.

An ideal VALiD based VTV achieves polarization insensitivity with a single stack. This can be obtained if the Eigenmodes of propagation are circularly polarized. Two parameters that have a great influence on light propagation properties are the birefringence and the pitch of the LC relative to the incident light wavelength. For normal incidence on a twisted cell, the Eigenmodes can be linearly, elliptically or circularly polarized. For a given birefringence, in the Mauguin limit, the characteristic pitch of the twist is much larger than the wavelength of the light resulting in linearly polarized Eigenmodes. As the pitch is reduced to the order of the wavelength of light, the modes become elliptically and finally circularly polarized.

Figure 4 shows the results of numerical simulations on planar aligned twisted cells. The birefringence and the cell gap were fixed. The director, however, underwent a continuous twist between the two surfaces. The polarization dependence of the transmittance was calculated for a number of twisted configurations ranging from 90 and 270 degrees. These translate to a d/p of 0.25 to 0.75 where d and p are the cell thickness and pitch, respectively. Increase in the total twist angle resulted in a significant reduction in the polarization dependence of transmittance.

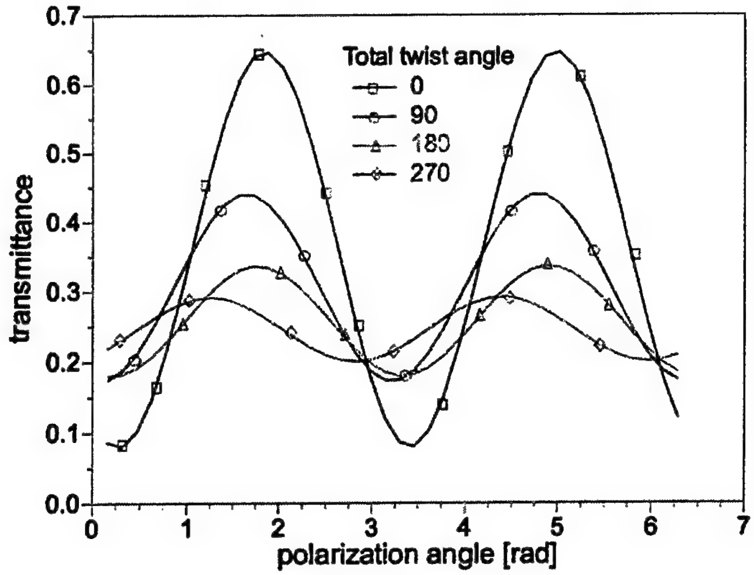


Figure 4. Calculation of the polarization dependence of the transmittance at 600nm for a twisted cell doped with dye for different total twist. The parameters used were those of the ZLI4119 host and 3% S428 Dye, cell thickness is 5.7.

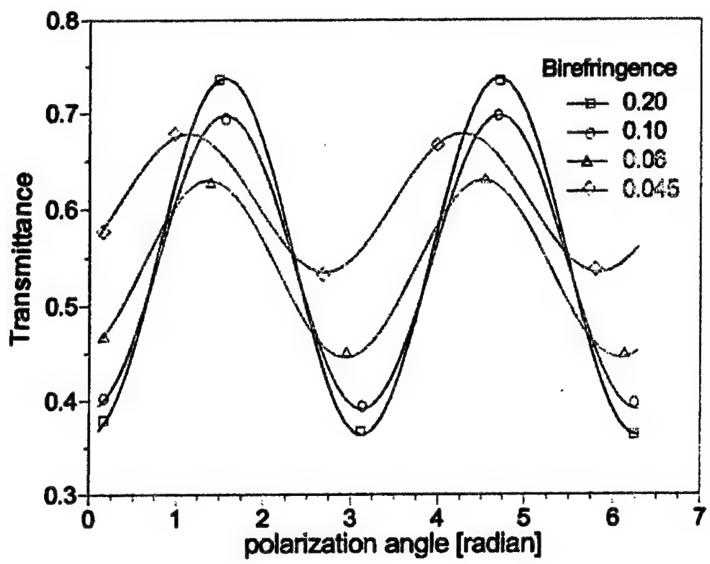


Figure 5. Calculation of polarization dependence of transmission for a TN cell with varying birefringence. Calculations use absorption data obtained from a LC doped with 1% of Sudan Black (DR =5 at 600nm).

Similarly, birefringence can have a large influence on the propagation modes of twisted liquid crystal cells. Figure 5 shows the transmission characteristics of a dye doped TN cell (90 degrees twist) as a function of the LC birefringence. All other parameters such as the pitch, sample thickness, and incident wavelength are kept constant. It can be seen that an improvement in polarization insensitivity can be obtained by lowering Δn for a twisted nematic cells.

The above results suggest a cell configuration with a small Δn and p. It should be noted, however, that for a complete gray scale control, the d/p of the cell cannot exceed a critical value. High d/p ratios result in formation of unwanted "strips" in the presence of moderate external fields and planar boundary condition. Therefore, it is desired to obtain the maximum d/p ratio below this critical value.

The maximum clear state transmission and the contrast ratio of the cell depend on the absorptive properties of the dyes used. These conditions, however, are interdependent. To demonstrate this point, a polarization insensitive system can be considered containing a positive DD with ordinary absorption α_{per}, extraordinary absorption α_{par} and a dichroic ratio, $DR=\alpha_{par}/\alpha_{per}$. For a given thickness, d, the polarization insensitivity suggests that an incident light will experience an absorption coefficient which is the average of the two principal absorption coefficients, $\alpha_{dark}= (\alpha_{per} +\alpha_{par})/2$. In the clear homeotropic state, transmission is dictated by the ordinary absorption coefficient, α_{per}. Consequently, the contrast ratio will be given by,

$$CR = T_{on}/T_{off} = \exp(-\alpha_{per}d)/\exp(- (\alpha_{per} +\alpha_{par})d/2) = [\exp(d\alpha_{per})]^{(DR-1)/2},$$

where T is the transmittance. It can be seen that the contrast ratio, $CR = [1/T_{on}]^{(DR-1)/2}$, depends on the clear state transmission and the dichroic ratio of the dye.

The swing in the transmission window can be significantly affected by the order parameter and the subsequent dichroic ratio of the dye. Figure 6 shows the clear and dark state achievable in this configuration.

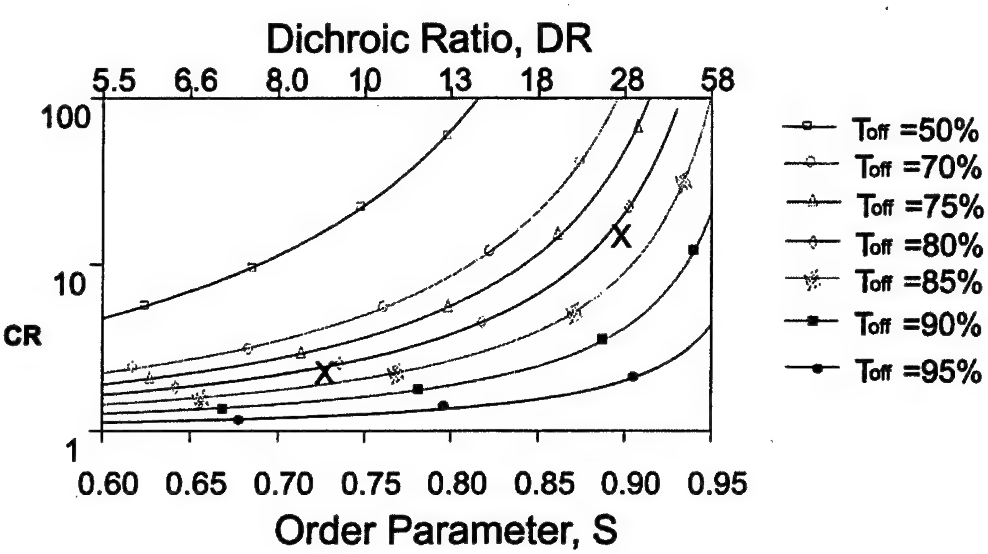


Figure 6. The ideal achievable contrast ratio for a given dye order parameter of clear state transmission

The formula for the contrast ratio, $CR=(1/T_{off})^{(DR-1)/2}$, assumes an ideal case of zero birefringence and surface anchoring and as such overestimates the real value. To get a more realistic value one needs to carry out a simulation of the electro-optic response. This was achieved by numerical simulation of the cell using the "Twist Cell Optics" program modified to configure to our geometry. This program was developed by Prof. J. Kelly of the Liquid Crystal Institute at Kent State University and is accepted within the LC community to have the greatest predictability for twisted nematic cell optics. The source code was provided to AMI to allow it to modify the program for modeling dichroic-based systems. In particular, the program was modified to model a homeotropic geometry with positive dichroic dyes and a negative LC host. This has a significant effect on the relative importance of the various parameters. As a first step, and to test the reliability of the model developed, the pure host with the chiral dopant was simulated. Measured and simulated spectral response in the ON and OFF state is shown in Figure 7. As the figure shows, excellent agreement can be obtained between theory and experiments. The results show that a number of parameters including natural pitch, birefringence, dispersion, pretilt angle, and cell gap have to be considered and measured independently to reduce the number of fitting parameters.

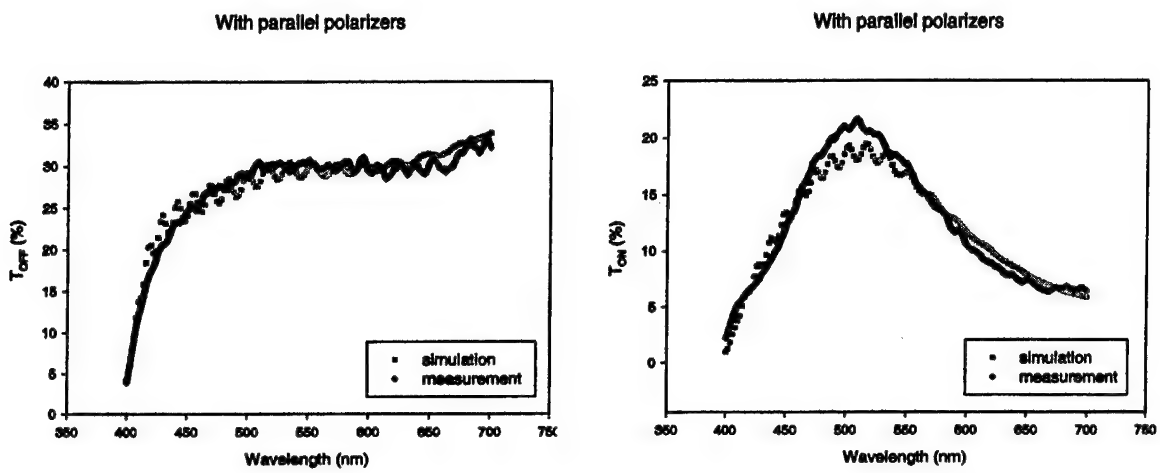


Figure 7. Simulated and measured spectral response of chiral host in the OFF and ON state.

The model was then optimized and corrected to account for transmission and reflections from the glass, ITO, the polyimide (PI) as well as the LC layer. Upon completion of the model, the program was tested against real parameter cells. It was found that without adjusting any material parameters, excellent agreement between calculated and measured data was achieved. In the calculation only the response of the dyed liquid crystal layer was modeled and the measured data was compensated for the reflection losses at the different interfaces.

Figure 8 shows the measured and calculated transmission spectra in the on and off states for two different dye mixture concentration. An excellent fit was achieved by adjusting the dye concentration value only which turned out to be slightly larger than the measured one.

Modeling of the system allowed us to study the effect of dye concentration on the achievable contrast ratio and transmission window. It is clearly seen from the results, shown in Figure 9, that in attempting to obtain optimal performance it is necessary to consider the transmission window as well as the contrast

ratio. In particular, while the contrast ratio monotonically increases with the dye concentration, the transmission window shows a maximum at around 5 weight percent (w%) of the specific dye used in this model. It should be noted that the calculation was carried out only for one selected mixture of dye-doped liquid crystal layer. Different optimized system is expected for different LC-dye formulation and as such the system must be continuously tested and optimized.

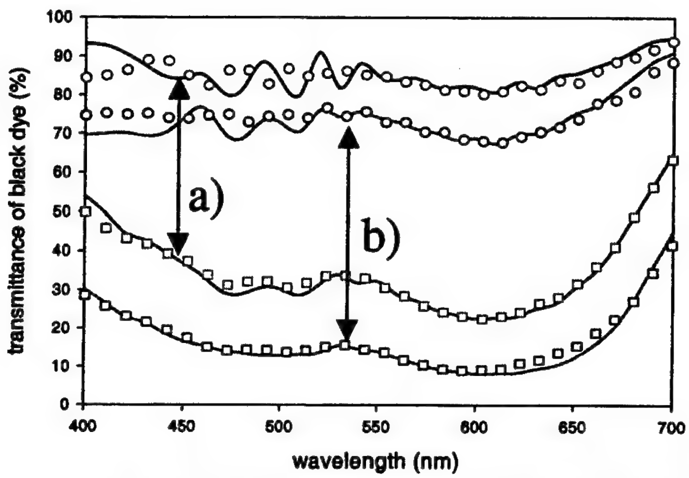


Figure 8. Measured and calculated (solid curves) spectral response in ON and OFF states of the new dichroic mixture with two different dye concentrations; a) 2.7w%, b) 5.1w%.

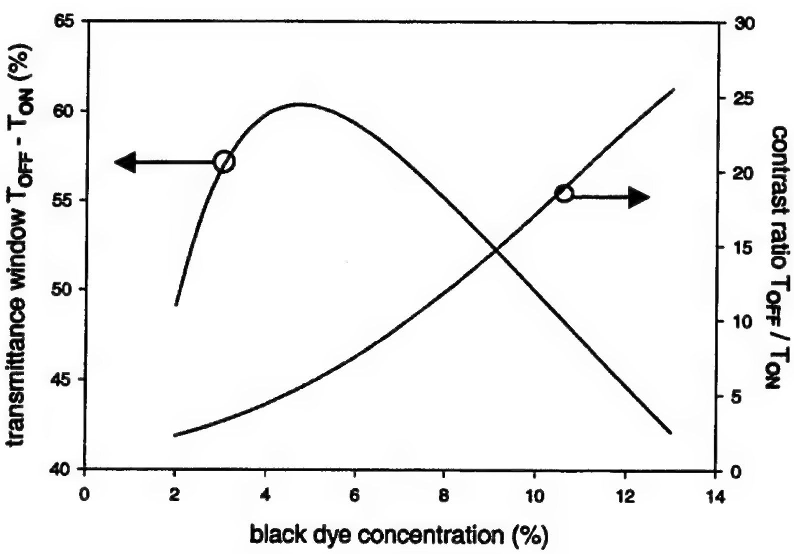


Figure 9. Model calculations of the contrast ratio and the transmittance window as a function of dye concentration.

As a parallel effort model calculations were run to determine the effects of a lowered dye concentration on the device performance. A series of simulation were performed to evaluate the electrooptic response of VALiD devices with a fixed thickness-to-pitch ratio, d/p=0.8, for a variety of black dye mixture concentrations and sample thicknesses. The results showed that the contrast ratio increases by increasing cell gap thickness and/or increasing dye content. This is to be expected since in most calculations, it is seen that the numerical values of the cell gap and dye concentrations appear together. As such, their product is determined to be the key parameter for optimization of the window and contrast. However, the maximum available transmission window decreases as the dye concentration decreases, and it can be only regained at larger thickness. However, since the presence of defects depend on the d/p and not the dye concentration, it is clear that there is an optimal dye concentration for a given pitch. Furthermore, due to the nature of light propagation in birefringent media, the polarization dependence of the attenuation in the ON state of the cell increases as the cell thickness increases. Although it is possible to optimize the thickness of the cell for best performance at any given dye concentration, the results suggest that it is more desirable to have a larger dye concentration in a thinner cell. This suggests that to optimize device performance, it is desirable to maintain the current device geometry while attempting to increase the dye concentration and therefore solubility.

In certain applications of VALiD such as commercial sunglasses and sport goggles, a polarization dependent attenuation in the ON state is more desirable. In these cases it would be more advantageous to

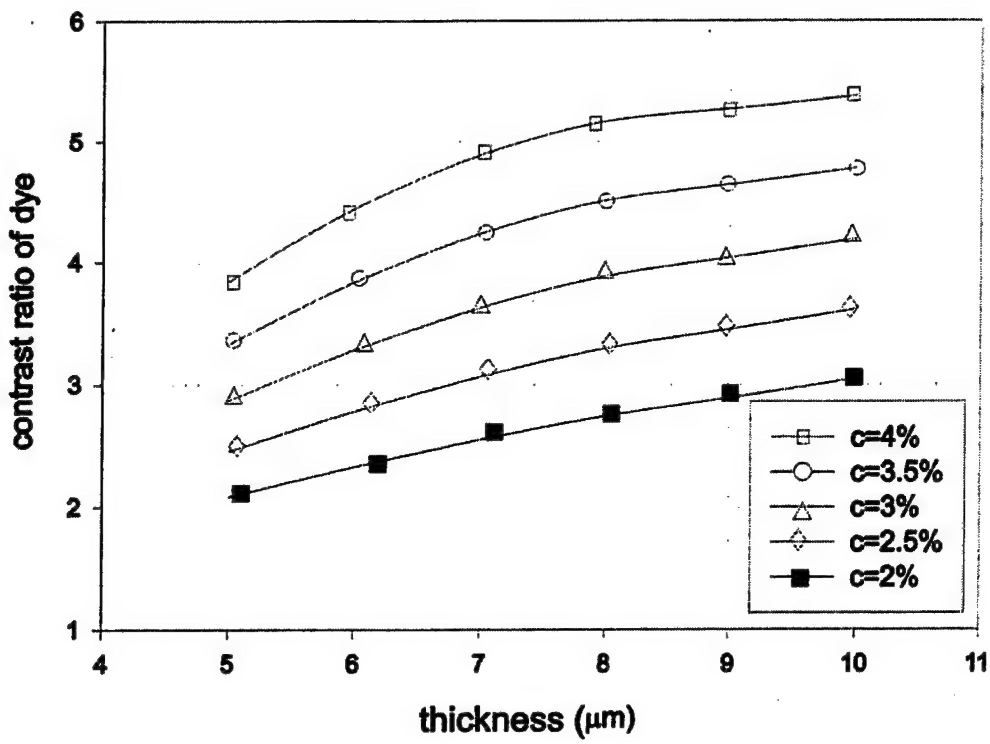


Figure 10. Contrast ratio as a function cell thickness at different dye concentrations

adjust the birefringence of the LC host to obtain the desired polarization sensitivity. This can be achieved by either (i) mixing two hosts with different birefringence or (ii) mixing highly birefringent additives into the host. In both cases the linear relationship of birefringence adding is assumed for the two component mixtures. In particular, $\Delta n_{mix} = c_{LC}\,\Delta n_{LC} + c_{add}\,\Delta n_{add}$, where Δn_{LC}, Δn_{add}, Δn_{mix} are the birefringence of the LC components, additive and mixture respectively. c_{LC} and c_{add} are the concentrations of the constituent components. We have found that the linear relationship does not follow the expected form for the order parameter of guest dye molecules. For example, mixing two hosts in 1:1 ratio resulted in dye order parameters which were very close to the lower order parameter measured in the individual hosts. Figures 10-12 summarize the results of these calculations.

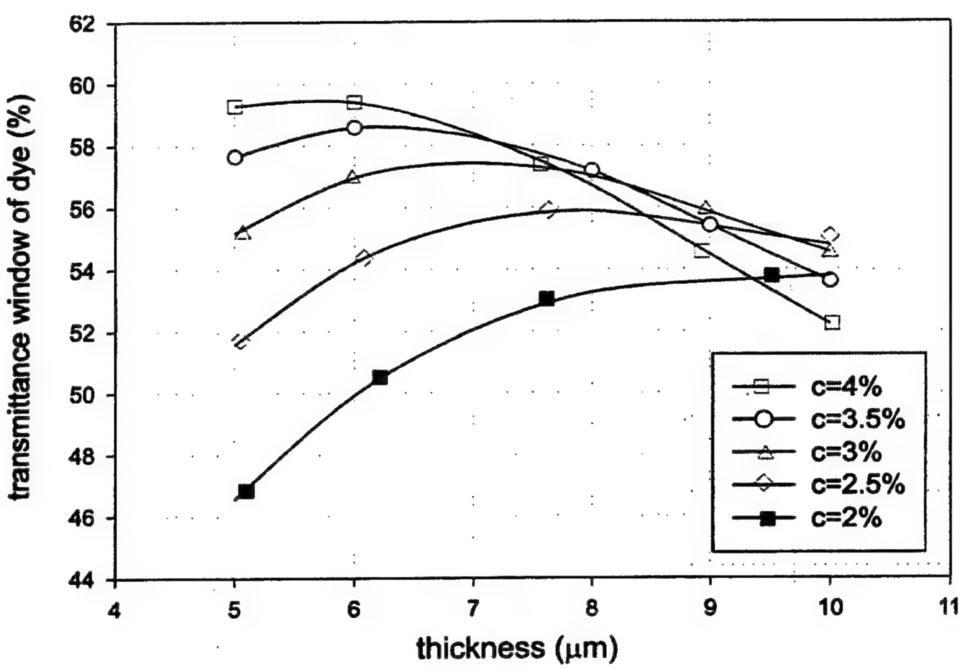


Figure 11. Transmission window as a function of cell thickness at different dye concentrations

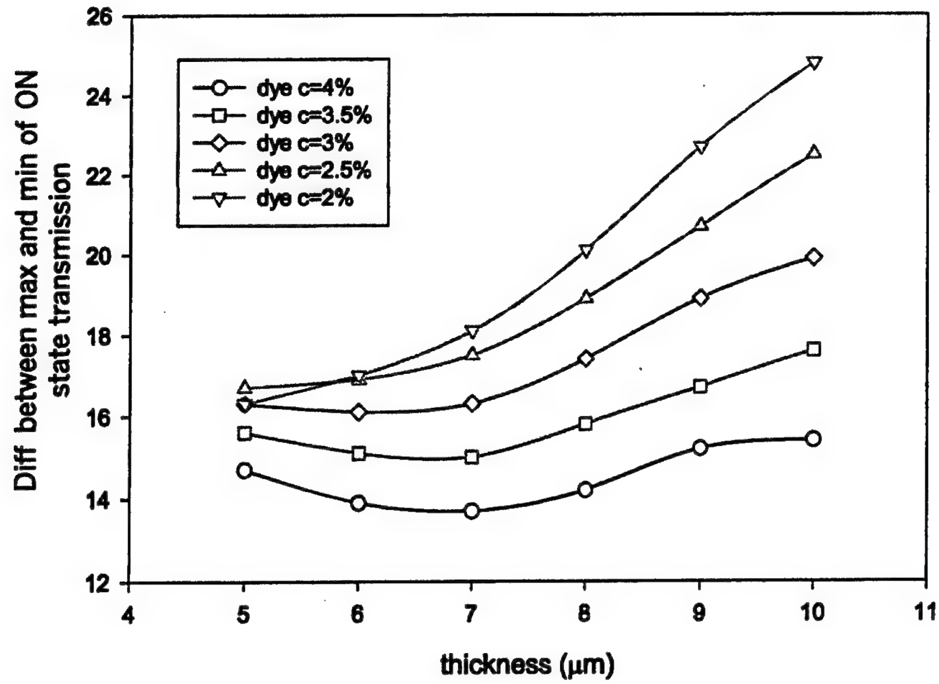


Figure 12. Difference between the maximum and minimum transmission of the cell in the ON state as a function of cell thickness at different dye concentrations

2.2. Material development

The goal of the material development effort was to increase the performance of the cell and develop the proper electronic switching to allow for optimal operation with low power consumption.

2.2.1. High order parameter dyes

As stated above, VALiD is based on a guest-host system in which the dichroic nature of the dye determines the transmission window swing. The key parameters, therefore, are the dichroic value of the dye in a given host, the concentration of the dye in the host, the birefringence of the liquid crystal, and the pitch of the mixture relative to the cell gap. Initially, AMI searched the existing commercial dyes and tested their performance in a variety of hosts.

Based on the data obtained through modeling, it was determined that dyes with high dichroic ratios are more important than dyes with high solubility. Figure 13 shows the typical absorption and dichroic properties of commercially available neutral gray Mitsui dye S428. The measurements were performed in a 9.1 micron planar homogenous cell with a dye concentration of 3w%. It can be seen that while the dye has a relatively large dichroic ratio (11:1), it is not entirely polarization independent and optically neutral. A shift in the chromaticity is observed, resulting in a purplish hue, at higher attenuation (a shift from x=0.328, y=0.326 to x=0.41, y=0.29 as measured in the CIE 1931 chromaticity diagram). For this system, and assuming a single layer twisted geometry with 80% transmission in the clear state (not including the 9% loss due to reflections), a contrast ratio of $CR=[1/0.8]^5=3$ was expected and obtained.

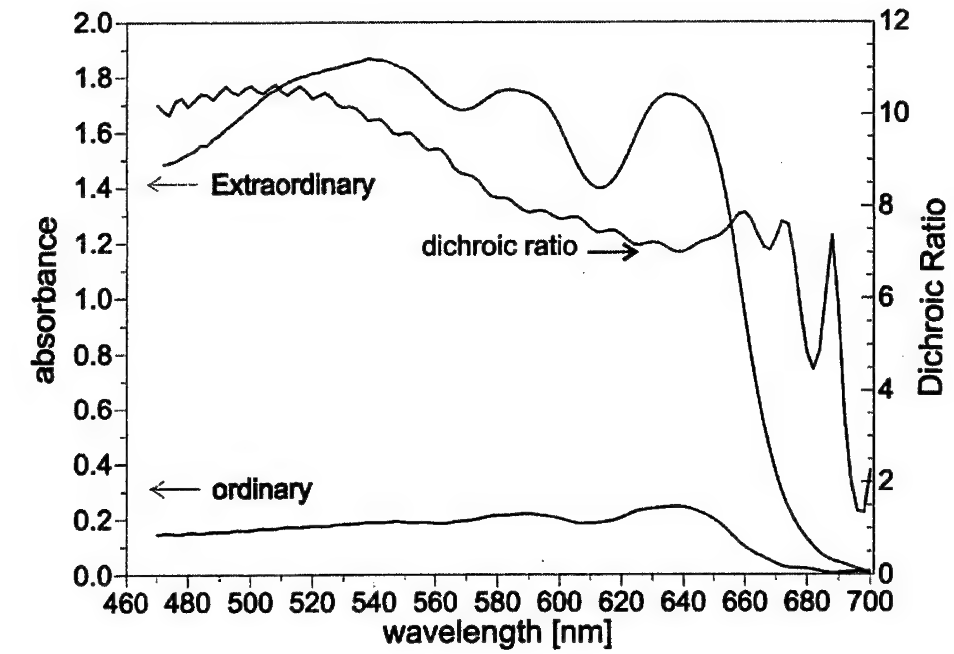


Figure 13. Ordinary, extraordinary, and dichroic ratio of Mitsui dye S428.

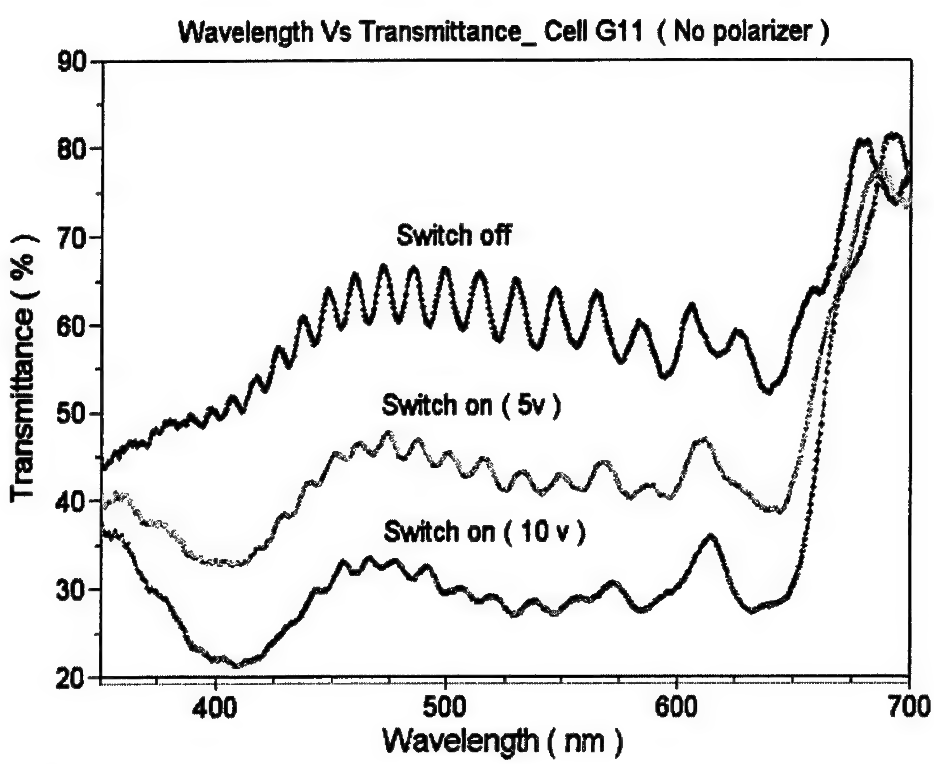


Figure 14. Absorption properties of commercial dyes in VALiD configuration.

Since the contrast ratio depends on the clear state transmission and the dichroic ratio, both parameters need to be considered. The former is a combination of the dye concentration and the cell thickness. Polarization insensitivity depends on the cell gap (as well as other parameters), therefore it is desirable to alter the concentration of the dye to achieve the required clear state transmission. Unfortunately, the dye solubility is limited and is dependent on the host LC. For S428 dye in the negative dielectric anisotropy host (ZLI2806), a solubility of 3w% was found.

Figure 14 shows the performance of the best commercially available dichroic dye (highest order parameter) in the VALiD configuration. It can be seen that while attenuation across the visible spectrum can be achieved, the contrast ratio is far from acceptable and as such novel dyes had to be identified.

The importance to the performance of VALiD of the order parameter of the dye and the very large variation in the contrast ratio and the transmission window associated with changes in the dichroic ratio of the dyes means that the order parameter measurements must be performed accurately. To achieve the tolerances required for accurate measurements, AMI's electro-optics facilities were expanded to enable automated measurements of the transmittance and absorption of broadband visible light from samples as a function of input light polarization and wavelength. The system uses an Ocean Optics spectrophotometer combined with computer controlled translation and rotation stages to control the polarization and the incident light. The computer controlled optical system was developed and programmed to measure the order parameter of the dye, the host, cell gap, polarization dependence, and the electro-optic response. Figure 15 shows schematic of the setup used for the evaluation.

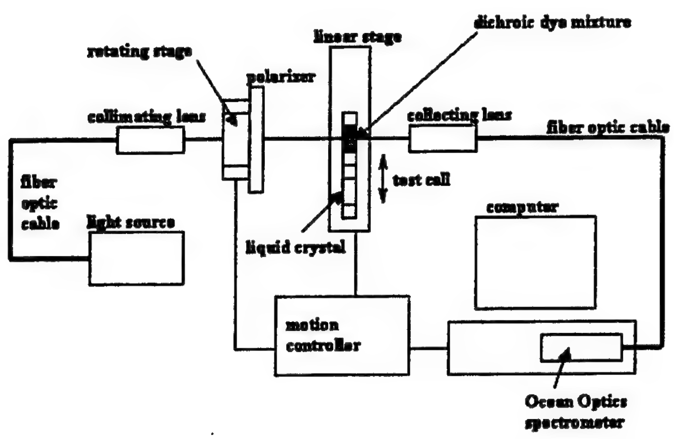


Figure 15. Schematic of the setup used for order parameter measurements of the dye

The electro-optical properties of a number of commercially available dichroic dyes were measured in different liquid crystalline host materials using this setup. It was determined that the commercial dye

performance fabricated for guest-host display applications did not provide sufficient performance for Air Force applications. Figure 16 shows the transmission of the clear and dark state of several "high" order parameter dyes in VALiD configuration. It was determined that the order parameter of the dyes in the host was within 0.7-0.8. The graph uses the ideal case for the calculation of the order parameter.

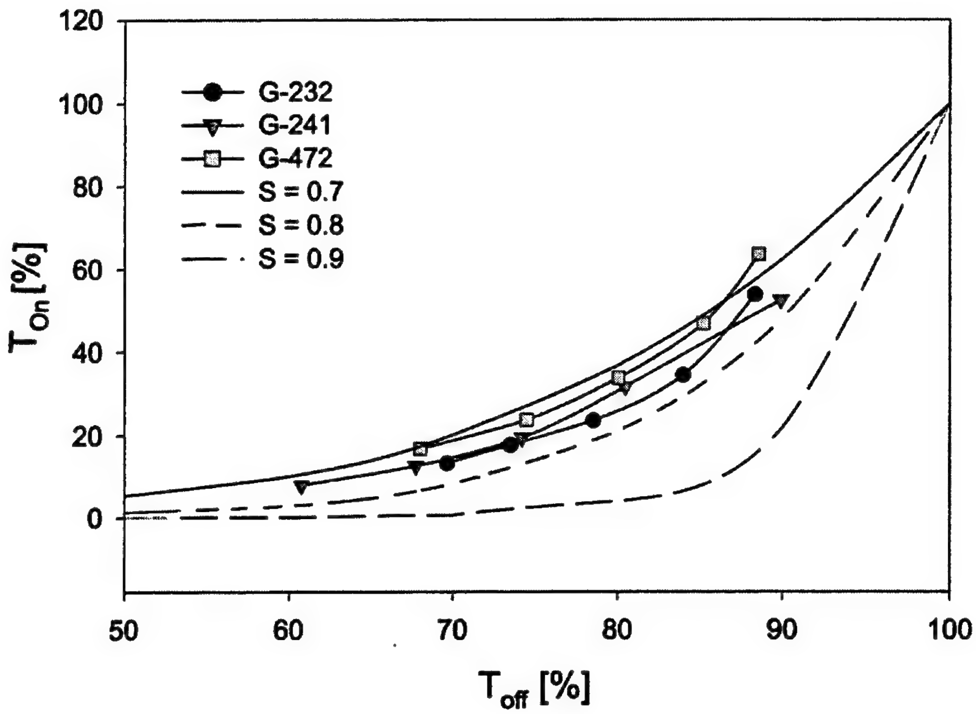


Figure 16. Performance and order parameter of several commercial dyes

The order parameter of the mixture is determined by the order parameter of both the dye and LC hosts. In other words, besides the inherent properties of the dye molecules, the dichroic ratio is strongly influenced by the order parameter of the liquid crystal host. In order to study the dye and host order parameter and its temperature dependence, the electro-optics facility was expanded by addition of an INSTEC temperature controlled stage to allow for control and change of the mixture temperature. The range of interest used was room temperature to mixture clearing point. Using the setup, the Stokes parameters of the light exiting the sample were measured at various temperatures. The temperature dependence of the birefringence calculated from these parameters was used to determine the order parameter of liquid crystal host and the dye. The result of a series of measurements is shown in Figure 17 where the order parameter of the pure host and the solute dye is shown as a function of temperature. It can be seen that the dye order parameter can be considerably higher than that of the liquid crystal host. Furthermore, the order parameter of the dye has a temperature dependence similar to that of the host liquid crystal. These observations suggest that there is not an inherent limitation on the dye order parameter and that it is possible to improve dye performance by proper choice of the liquid crystal host.

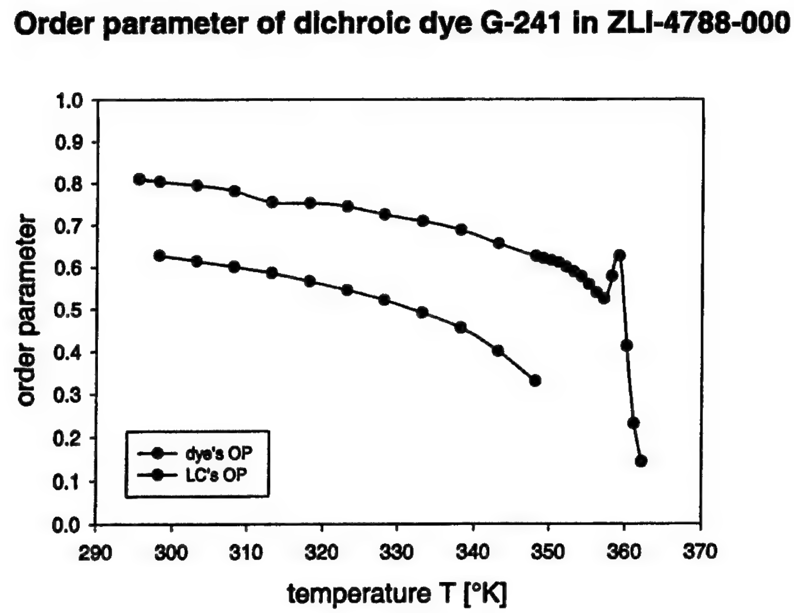


Figure 17. Order parameter of liquid crystal host and dichroic dye vs. temperature.

Based on the above analysis, a significant effort and emphasis was placed on development of novel dyes with the aim of achieving high order parameters. A detailed study of the literature revealed that there had been a number of reports of dyes with high order parameters. AMI purchased or synthesized some of these dyes in conjunction with PPG industries. However, it was found that the measurements of the order parameters were not consistent with reported numbers. In addition, it was determined that the solubility of the dyes was low in the negative host of VALiD.

Given the results for commercial dyes, AMI embarked in a rigorous dye development effort. It synthesized several dyes and tested each in the variety of hosts. The results were then used to modify and re-synthesize new dyes. This long process was continued throughout the past three years. The results were that AMI has the highest verifiably tested order parameter dyes. Figure 18 shows the transmission in the clear and dark state of AMI's new dyes. The transmission window corresponds to a dye of order parameter equal to 0.85. It is important to note the clear state transmission plateaus. This means that to achieve the ranges where the clear state of the dye is greater than 80%, the dark state transmission would be >35%. Therefore, to achieve ophthalmic grade dyes, higher order parameter dyes are needed.

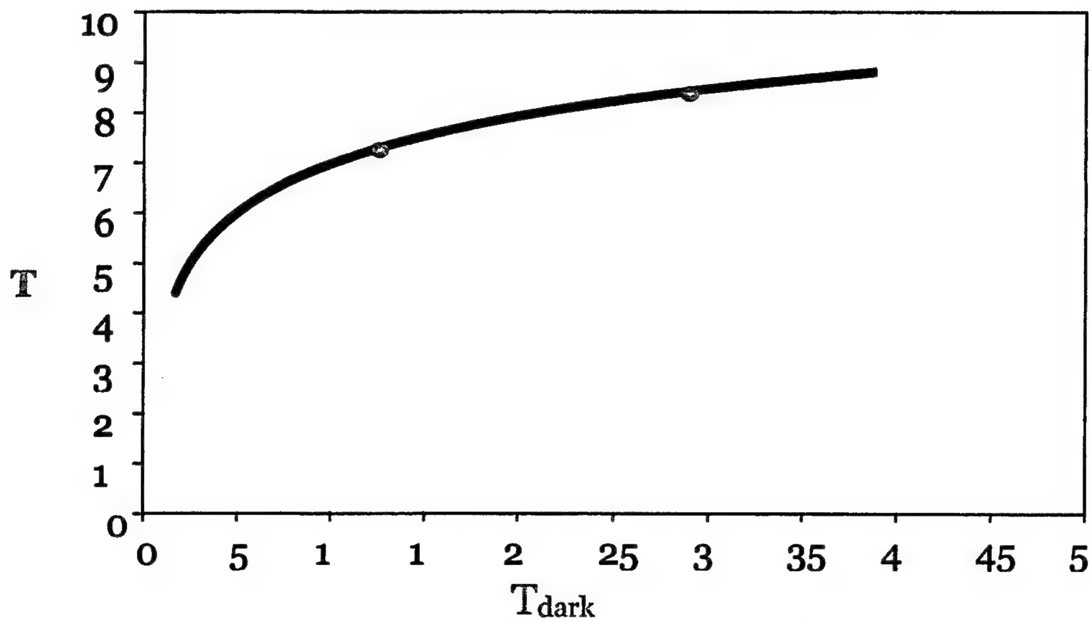


Figure 18. The transmission in the clear and dark states of the new AMI dye. The solid line corresponds to the theoretical calculations of dyes with order parameter of 0.85

Since color neutrality is a requirement of VTV, effort was then placed on development of different color dyes to achieve absorption across the entire visible spectrum. The high order parameter dyes developed were used as a basis for development of dyes with different dipole transition moment amplitudes and energies. This required new chemistry since the nature of dyes across the visible spectrum is quite different. In particular, given that the dichroic dyes have to have great purity, the materials and processes used for synthesis were quite different. For example, blue dyes are in general more ionic and require polar solvents whereas yellow dyes are more organic and require organic solvents. A number of different dyes were synthesized. It was found that even slight changes in the dye groups can have a significant effect on the overall order parameter.

Figure 19 shows the absorption bands of some of the high order parameter dyes we synthesized. It can be seen that absorption across the entire visible spectrum can be achieved by mixing the dyes. In addition, the dyes can be used individually for applications where a change in the hue is desirable. These dyes were used to obtain high order parameter, neutral mixtures which met the 60%-15% transmission window required for daytime use of a VTV.

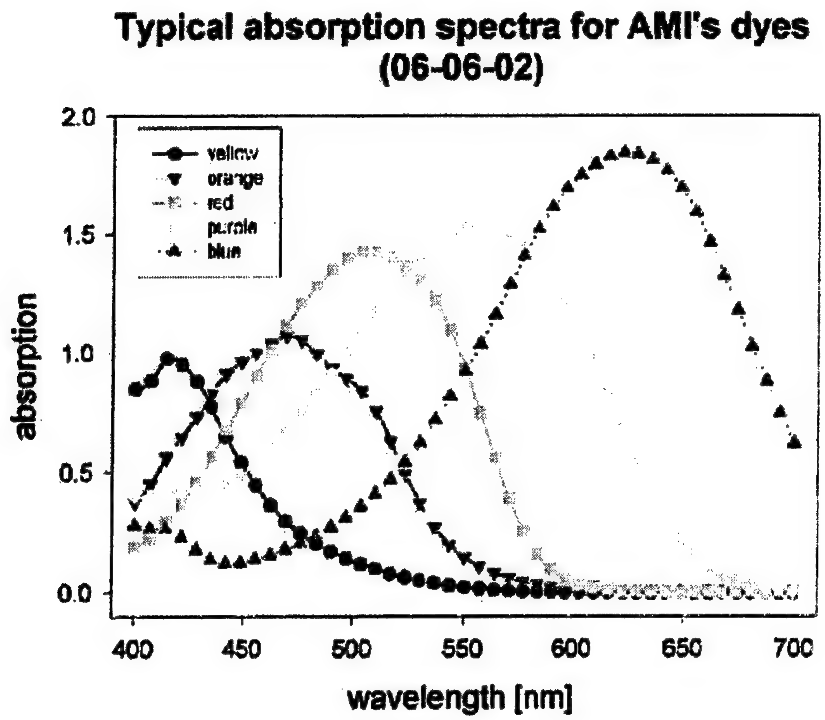


Figure 19. The absorption spectra of AMI's high order parameter dyes. Black dyes can be obtained by mixing a variety of dyes with different absorption across the visible spectrum.

2.2.1. Electro-optics of the mixtures

The mixtures used for VALiD must posses the proper electro-optic performance as well as the large transmission swing. In particular, they must use a low voltage for driving, have a fast response time, and consume very low power. Therefore, the order parameter dye is one component of the mixture. The other main component, LC, must have the correct optical properties which are a function of both the physical properties of the host such as dielectric anisotropy, birefringence etc. as well as chemical properties such as chemical interaction with the surface and solvent characteristics for the additives including the dye.

An important parameter is suppression of bistability. In LC cells with chiral dopants, such as cholesteric, STN, etc. as the pitch is shortened beyond a threshold, bistability in the electro-optics response is observed. This bistability is useful for display applications but can be detrimental to the eyewear application of the system. As such, it is essential to ensure that the mixture lacks the characteristics that lead to bistability. Since the optical properties of the mixture are dictated by the constituents such as chiral dopant and birefringence, this optimization must be performed in conjunction with the optical experiments.

Figure 20 shows the electro-optic response of the mixture, which possesses a high transmission window and fast response. It can be seen that while the system does not exhibit bistability its electro-optic

response demonstrates that its physical properties are similar to those of bistable systems. Therefore, the optimization has reached a maximum.

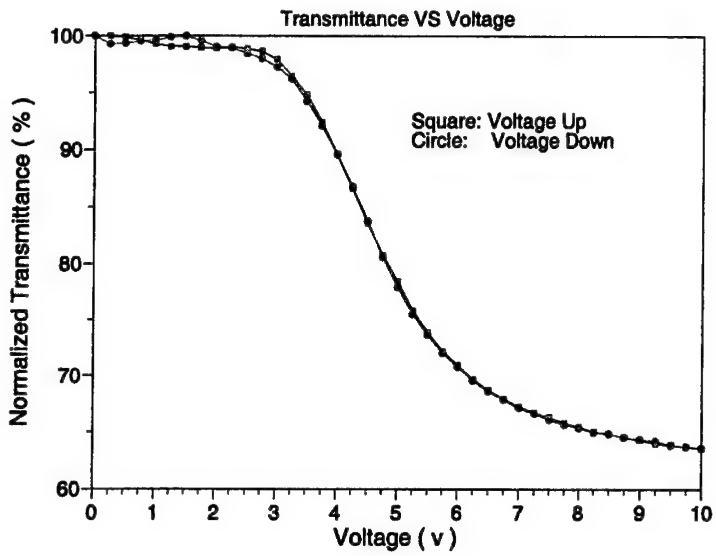


Figure 20. The electro-optical response of the VALiD cell. Note that the system does not exhibit bistbility.

This optimization had a significant effect on the response time of the system. While the VTV response requirement is less than a second, it will be beneficial to reduce the response time as much as possible. This has two advantages. The first is that it will allow the system to be used for fast modulations which is needed if the pilot encounters varying ambient light. Examples of this include moving through a cloud formation. The second advantage is that exceeding the performance on one criterion allows future improvement in the other aspects. In particular, if the response has been reduced from 1 second to 0.1 second, this allows the mixture to be reformulated for higher order parameter at the expense of response time so that at the conclusion the 0.1 s mixture is slowed to 0.8s while gaining higher order parameters. This viability of this scenario is currently under investigation.

Figures 21(a) and (b) show the electro-optic response of the mixture at the beginning of the program as well as the current status. It can be seen that the response time has been reduced by one order of magnitude while as stated above the order parameter has increased from 0.77 to 0.85. This fast response if not needed for VTV but will allow AMI to develop the next generation mixtures.

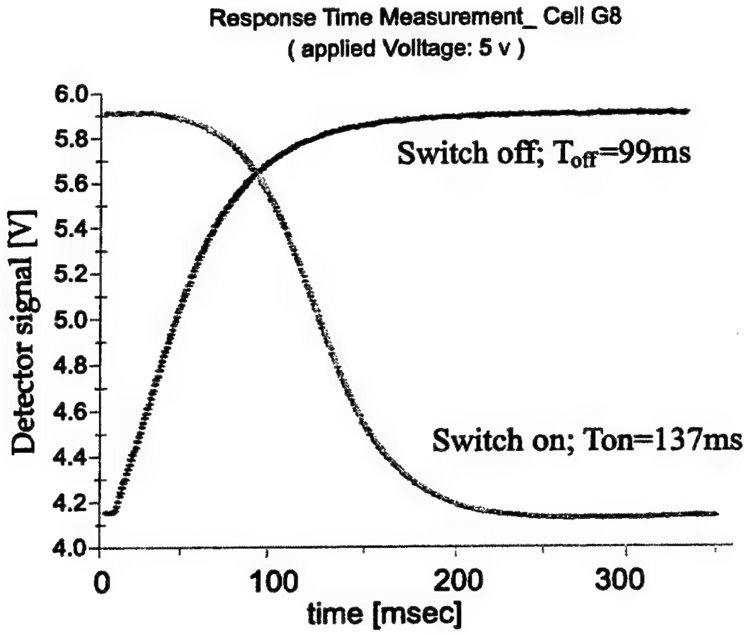


Figure 21a. Electro-optic response of the VALiD cell after phase I.

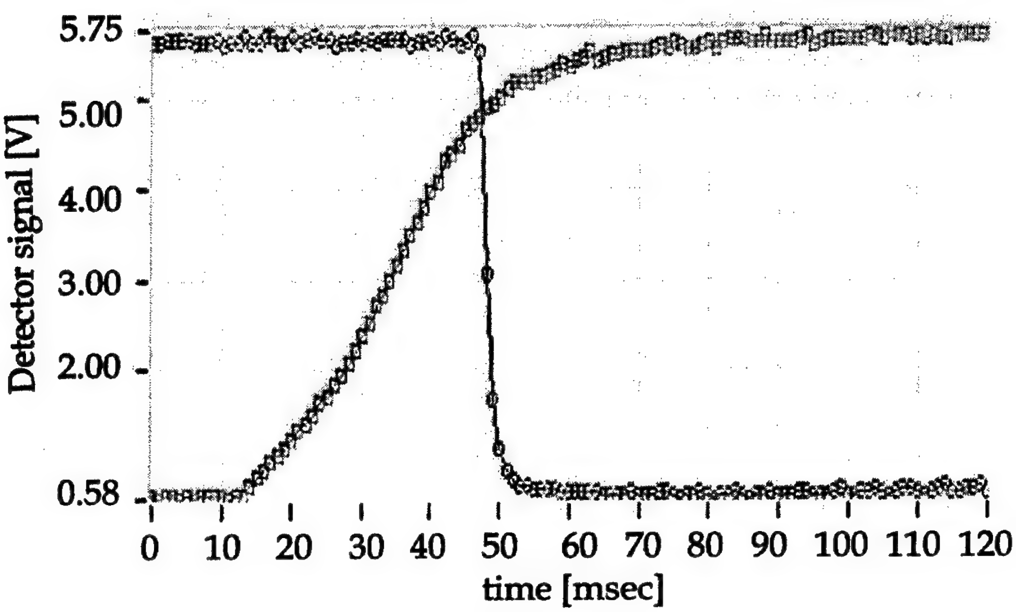


Figure 21b. Current electro-optic response of the VALiD cell with new formulation.

2.3 Processing development and prototyping

VTV must be implemented on doubly curved plastic substrates. Currently there are no LC devices which are implemented on these substrates. As such, AMI had to invent new methods to achieve this goal. During the past five years, AMI has become the leader in implementation of LC on doubly curved substrates.

To appreciate the challenges involved, it is necessary to understand the major differences between processing conventional LCDs and a VTV. An LC device, in general will have a cross section as shown in Figure 22. In particular, the substrate (glass, plastic) is coated with a transparent conductive (ITO), followed by an insulating layer (silicon dioxide), then the alignment layer which dictates the state of the LC in the unenergized state (homeotropic). The cell spacing is dictated by spacers whose diameter matches the required spacing. The dimensions of the different components are significantly different. In particular, the substrate is ~1mm (1000 micron), the ITO, passivation and alignment layers are ~1000A (0.1 microns) and the spacers are ~5 microns. Therefore the system has a range of 10,000:1 in dimensions.

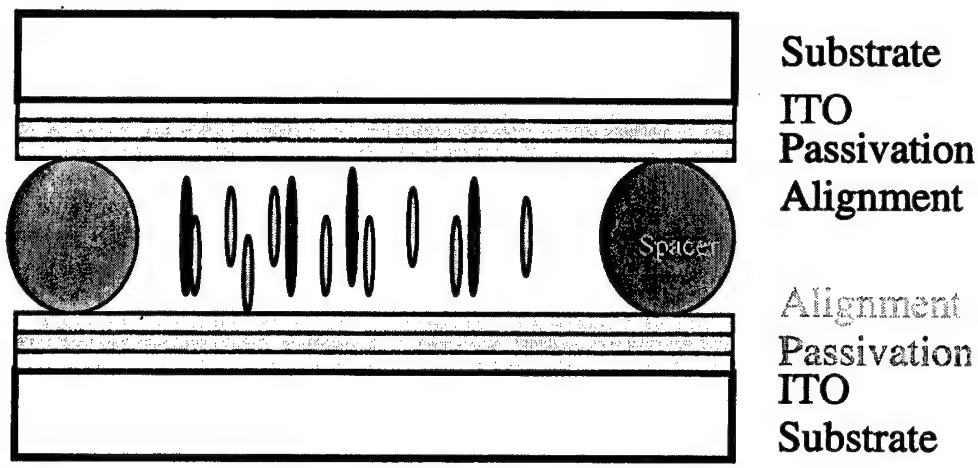


Figure 22. Cross section of LC cell. Note that the dimensions are not drawn to scale.

LC devices have been made using glass substrates for the past three decades. Therefore, the layers and their processing have been optimized for these substrates. However, when the substrate is changed from glass to plastic, all layers and their processing parameters have to be examined and modified. It is for this very reason that plastic based LCD devices have not been commercially available. In particular, the main variations are outlined in Table 3.

Table 3: Processing parameter difference between LCD and VTV

	LCD	VTV
Substrate	Glass	Plastic
Curvature	Flat	Curved
Spacers	Glass	Plastic
Chemical Resistance	Stable	Unstable
ITO properties	Good	Poor
Gasket seal glue	Thermal	UV
Rubbing	Strong	Soft
Cleaning	Megasonic	Ultrasonic
Filling	Strong Vacuum	Weak Vacuum
Cutting	Scriber	Mold/laser
Connection	Solder	Adhesive

Figure 23 shows the possible substrates that can be used for this application. It can be seen that the substrates are classified into flexible and rigid substrates. Each substrate has a unique advantage and disadvantage for VTV applications, as will become apparent.

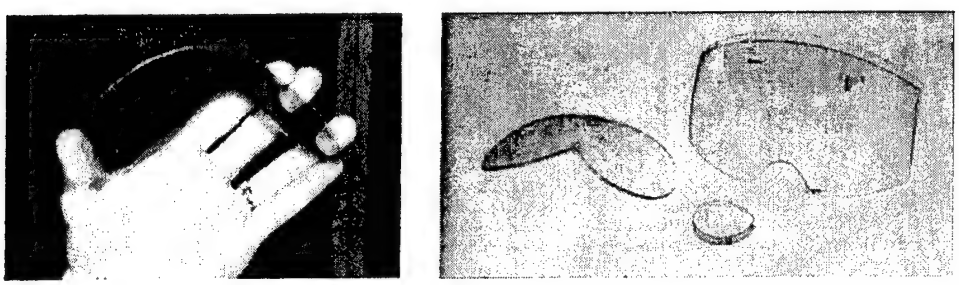
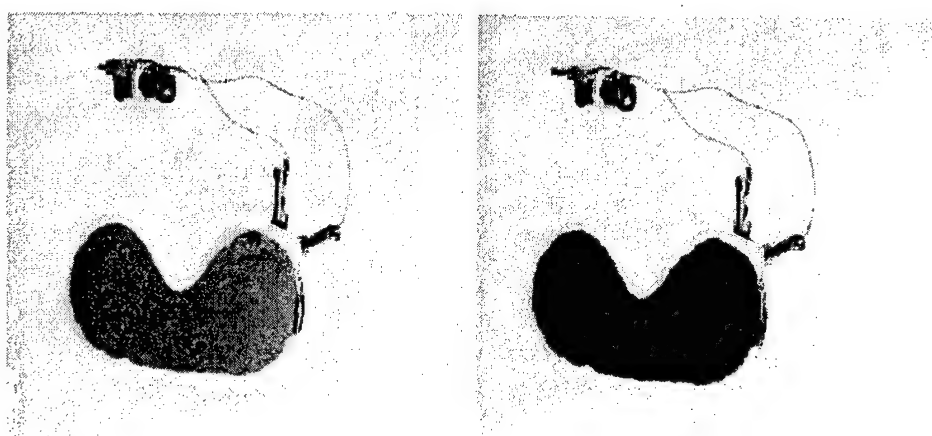


Figure 23. Possible choices of base substrate for using VALiD for VTV applications. (a) flexible ITO coated plastic such as PET, and (b) rigid ITO coated plastic including CR39, PC.

Testing of the FC-VALiD configuration and optimization of the relevant parameters were performed using flat glass substrates. Since the final system must be implemented on Air Force issued plastic visors it was necessary to perform a significant redesign on the conventional processing techniques for liquid crystal based devices. The progression from flat glass to doubly curved plastic was divided into different stages. The first involved the use of flat glass to develop and test appropriate processing materials relevant to plastic substrate processing. Issues that were considered included the glass transition temperature of plastic substrates, chemical reactivity of processing material, and curing temperatures of the alignment layer. Furthermore, processing parameters such as alignment layer thickness and spacer deposition were tested for FC-VALiD with glass substrates.

2.3.1 Flexible substrate processing

The second stage involved implementation on flat plastic substrates. The materials and processing parameters obtained were used to test FC-VALiD on flat PET substrates. This choice of substrate was dictated by the commercial availability of ITO-coated plastic. ITO-coated PET substrates were cut and cleaned using an ultrasonic cleaner. A homeotropic alignment layer was spun onto the substrates and allowed to cure. The substrates were assembled using 5-micron spacers and vacuum filled. The electro-optic properties of the FC-VALiD were used to investigate the processing parameters, such as alignment layer uniformity and spacer density. The materials and processes identified during the first stage were re-examined and optimized. Figure 24 shows the results of the assembled cells. The shape chosen was that of the Army SWD goggle. These goggles are standard issue for protection against Sun Wind and Dust.



Goggle lens in OFF state

Goggle lens in ON state

Figure 24. VALiD on flat flexible substrates.

Cylindrical VALiD can be achieved by either using two conformal cylindrical substrates or two flexible flat substrates. Given the success, it was decided to use flat substrates because the processing techniques developed earlier would require less modification. Therefore, this stage involved implementation of material and processing on flexible PET substrates. The substrates used were 7-mil, ITO-coated PET from Cortauld plastics. The substrates were cleaned and coated with a homeotropic alignment layer using spin coating techniques. They were then assembled using 5-micron spacers and sealed with a UV-curable epoxy. The cell was vacuum-filled with a mixture of liquid crystal and a Mitsui S-428 black dichroic dye. The cells showed flexibility and were conformed to the cylindrical shape of the Army SWD goggles. Figure 25 shows the FC-VALiD based goggles obtained.

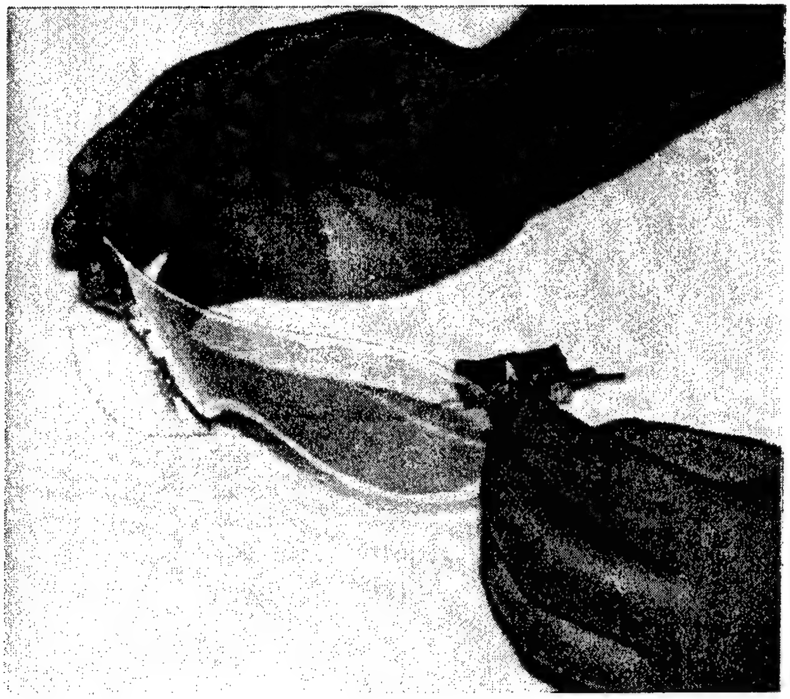


Figure 25. An FC-VALiD based system implemented on flexible substrate for use in SWD goggle.

2.3.1 Curved substrate processing

Air Force visors, unlike the Army SWD goggles, are curved in both directions. There is a significant jump in moving from a cylindrical curvature to a double curvature. This is primarily due to the change in the area associated with a complex curve. Unlike the cylindrical cells, a flat cell cannot be made to fit a visor without significant alteration in its area. Therefore, it is not possible to use flat substrates to obtain FC-VALiD based VTVs.

To obtain doubly curved FC-VALiD, it was necessary to use two conformal substrates. This required a significant alteration in processing techniques. To develop these techniques, specially designed spherically shaped, conformal lenses coated with ITO were used. The spherical nature of the lenses allows for rotation symmetry during the assembly process. The two halves were tested for conformity prior to processing. It was found that, despite careful manufacturing conditions, the natural conformity was not within the tolerances required for liquid-crystal based devices. Thus, it was necessary to reshape the substrates to achieve conformity. In addition, novel processing methods had to be developed because conventional techniques such as spin coating are designed for flat substrates. These methods were developed and enabled us to implement FC-VALiD on spherical lenses with performance matching that obtained on flat glass. Figure 26 shows the VALiD system fabricated using the above process. The lenses were ophthalmic grade CR39 lenses.

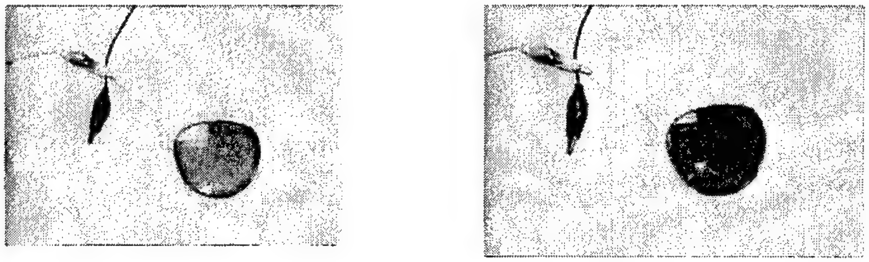


Figure 26. VALiD on doubly curved rigid substrates.

To move from the small lenses to Air Force visors required a change in the processing method. For example, spin coating of a visor is impossible due to the curvature. However, we were able to demonstrate, for the first time, implementation of a liquid crystal technology on large area doubly curved plastic substrates. A base-cap visor pair was purchased form AOtec LLC. Although the base-cap pairs are stackable, they are not conformal to within the tolerances required for liquid-crystal based technologies. Furthermore, the toroidal nature of the visors means that the processing techniques must also be rotationally sensitive. As with the lenses, the base-cap visor pairs were processed and forced to conform to a 1-micron tolerance. They were coated with low resistance ITO followed by our homeotropic alignment layer and assembled using 5-micron spacers. The visor assembly was then vacuum filled with the LC/dye mixture and sealed. The dye used was the neutral brown color with moderate order parameter components. The mixture was tuned to allow a transmission range of 60%-15%. This window meets the requirement for daytime use by the pilots. The system was externally wired and driven by a 9V battery. Figure 27 shows the visor with FC-VALiD system.

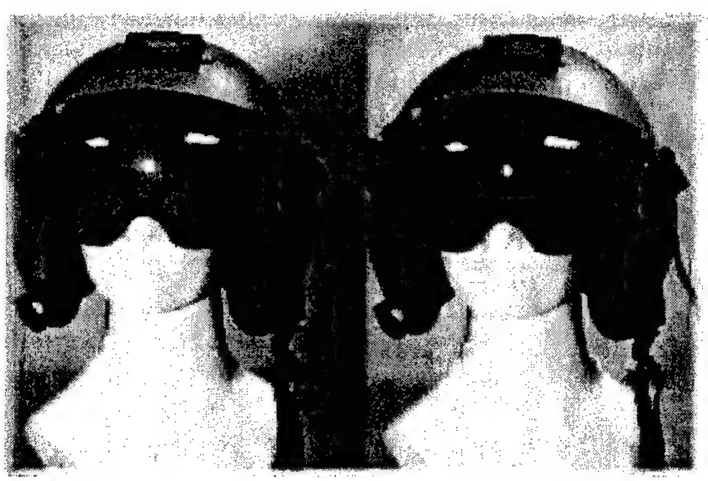


Figure 27. An HGU-55/P helmet visor with FC-VALiD system.

Although this system has been demonstrated, there are a number of issues that needed to be addressed. In addition to materials performance, the conformality of the substrates is an essential feature of the

device and requires tight control. This, along with the novel processing methods required, make it a challenging task to develop a completely controllable visor system.

The visor was sent to the Air Force for evaluation within an HMD system. The experiments demonstrated presence of stray reflections from the LC layers, as well as an enhanced parallax associated with the base-cap pair

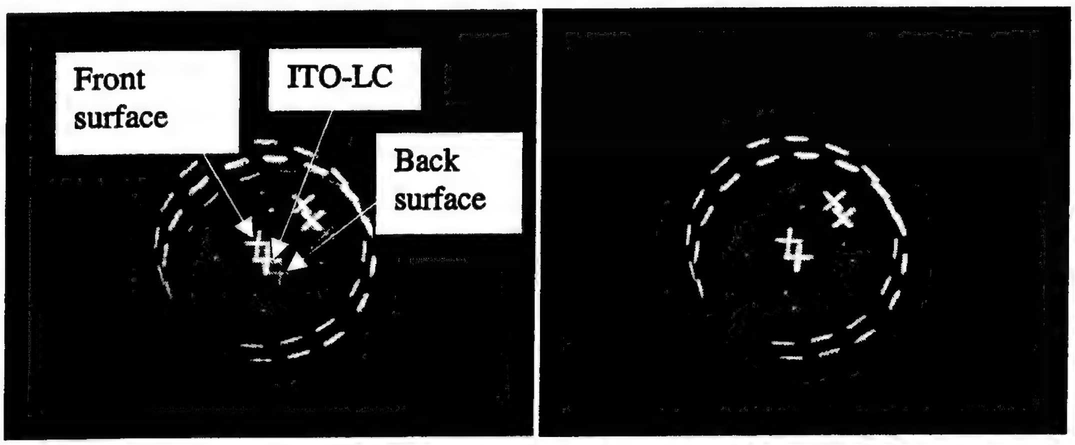


Figure 28. Reflections from the ***uncoated*** *VTV in dark room with HMD signal (a) VTV in the clear state, (b) VTV in the dark state.*

Figure 28 shows the reflection of the HMD source from a VTV without the internal AR coating. It can be seen that three reflections exist. The first is from the air-plastic interface of the front surface of the visor. The second is from the liquid crystal layer (including the ITO, PI etc.) and the third, more faint, is from the back surface of the VTV at the air-plastic interface. The presence of three reflections is due to the large thickness of the base-cap pairs. The 1mm separation between the different reflecting surfaces results in parallax and appearance of three distinct reflection spots. It should be noted that the second reflection is comprised of reflection from plastic-ITO, ITO-LC, a second ITO-LC (on the opposite surface of the cell) and a second ITO-plastic. However, since these layers are ultra thin (5 microns, total), it is expected that all the internal reflections fall on top of each other and do not exhibit parallax.

With this in mind, the reflection characteristics from the AR coated visors were studied. It was determined that the thickness of the passivation and ITO layers can be tuned so as to minimize reflections from within the VTV layer. These coatings had to be especially vacuum deposited on bare visor substrates prior to assembly. The coatings were designed by General Vacuum Inc. based on the materials and thickness needed for broadband AR coating. AMI fabricated a VTV using these coated visors where additional layers were coated on top of the ITO layer to reduce the internal reflection from the visor. The visor was sent to Wright-Patterson AFB for evaluation.

It was determined that while the internal reflection is reduced, the ghost image is still present and in the current state is unacceptable for HMD applications. When the VTV is turned on and in the dark state, it can be seen that (i) the second reflection is slightly weaker and (ii) the third reflection is almost

invisible. This is consistent with the observed function of the VTV. The on state of the VTV results in the absorption of incident light. The first reflection from air-plastic interface remains unchanged. The second reflection intensity is reduced but not eliminated. The components from the first plastic-ITO and ITO-LC layers are reflected without being subject to the absorptive LC layer. The second ITO-LC and ITO-plastic, however, undergo transmission through the absorbing layer and as such are reduced/ eliminated. The third reflection from the outside surface of the visor at the plastic-air interface has to travel through the absorbing material and as such is eliminated.

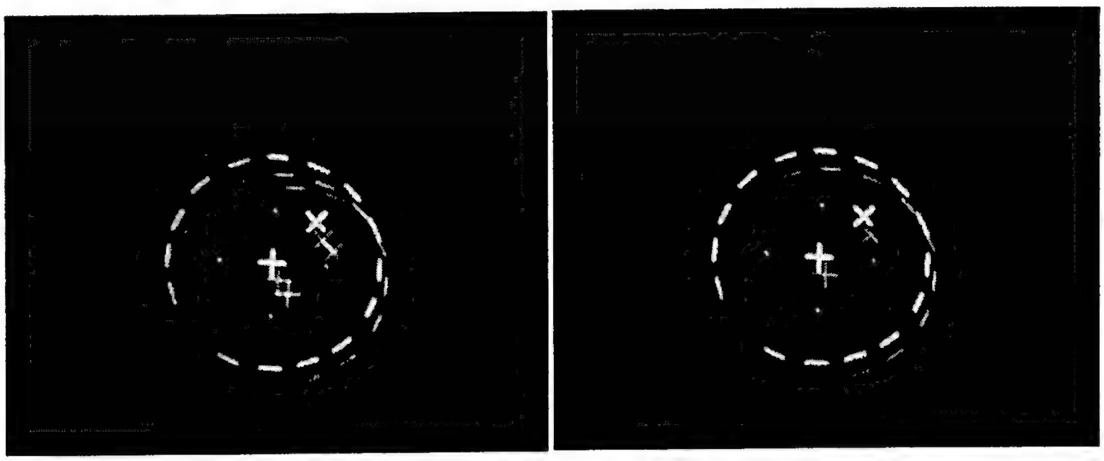


*Figure 29. Reflections from the **coated** VTV in dark room with HMD signal (a) VTV in the clear state, (b) VTV in the dark state.*

Figure 29 shows the reflection obtained from the assembled visor with internal AR coating. It can be seen that the internal AR coating, did not completely eliminate reflections. However, it can be seen the reflection is significantly reduced. In particular, comparing Figures 28 and 29 suggests that the reflection from the internal layer after the AR coating is of the same order of magnitude as the reflection from the back surface. Since the back surface reflection undergoes transmission through the absorbing state (even in the clear state this is only 70%), it can be estimated that the internal AR coating reflects approx 1-2%. This is to be expected since the coating was designed for normal transmission and on glass substrates. The large curvature of the visors prohibits uniform coating and therefore results in reduction of performance.

One solution to the problem is to AR coat the inside and outside surfaces of the visor and leaves the internal surface as the reflecting surface. However, this method will not completely eliminate reflection from the front and back surfaces and due to the large parallax, these small but non-zero reflections will appear as ghost images. Furthermore, this adds significant cost to the visor.

The alternative solution is to use a thin film as one of the substrates. In that case, the reflection from the VTV LC layer will be coincident with the front or back surface (depending on the location of the film). Additional AR coating is only needed for one of the surfaces if higher contrast is desired. This introduces significant cost saving.

This is the subject of AMI's next research efforts.

3. Current state and future development

By the end of the project, AMI demonstrated that it can fabricate VTVs. However there exists undesired reflections from within the VTV. Furthermore, even with internal AR coating, ghost images appear in the VTV. These images are less intense than the front surface reflection and are displaced from each other significantly due to parallax. The parallax makes the ghost images visible in dark ambient lighting conditions and as such reduces the performance of the HMD and thus must be minimized or eliminated. The results suggest that while using internal AR coatings does reduce the reflection, the presence of parallax plays a more significant role than the intensity of reflections from various surfaces. A solution to the problem is to use a thin (less than 0.3 mm), film as one of the substrates. This reduces the parallax due the VTV LC layer and effectively reduces the parasitic reflections. The remaining reflections are those from font and back surfaces. To minimize the reflection from the back surface, a tinted visor or AR coating must be used.

Thus far, AMI had focused on using two rigid, semi-conformal substrates. These were not conformal to the required levels and were existing commercial product from AOtec. This product used two, 1 mm thick, pieces of plastic for a base and caps. The resulting 2 mm thick visor exhibited a large parallax for reflected light. In addition, it has been suggested that the rigid substrates reduce the lifetime of the VTV by stress-induced delamination. The main reason for using these base-cap pairs was that there were no other means of obtaining conformal substrates such as a thin film material capable of matching the visor form. As such, AMI will focus on developing a method for obtaining the thin film required as well as initiating possible fabrication and assembly methods.

To meet this goal, several sheets of ITO coated PET and polycarbonate films were purchased from Applied Films. The films were cut into 2" pieces and were subjected to thermoforming. The parameters used were those reported earlier. The films were inspected for haze and conductivity after thermoforming. The results suggested that the process and curvatures required results in micro cracks of the ITO film and subsequent reduction in conductivity as well as excessive optical haze.

Several attempts at thermoforming were made and are still in progress. The thermo-forming parameters were adjusted for PET as well as polycarbonate. The critical parameters in obtaining uniform forming were found to be temperature and pressure *CYCLE* rather than the absolute values imparted to the substrates. The main issue thus far is that the ITO layer during thermoforming undergoes significant reduction in optical and electrical performance which as stated earlier is attributed to introduction of cracks in the ITO film during thermoforming.

To overcome this issue, AMI has initiated a program to thermoform a single flexible plastic substrate *PRIOR* to coating it with conducting material. In this approach, a thin plastic substrate is thermoformed to the desired curvature. The substrate is then coated with the conductive material and the cells are assembled. Figure 30 shows the initial apparatus used to heat the substrate under pressure prior to thermoforming. The clamps allowed for a fixed pressure to the mold which was placed in the oven for two hours at a variety of temperatures. The glass transition temperature for the plastic was determined by this simple method and by visual inspection of the deformation.

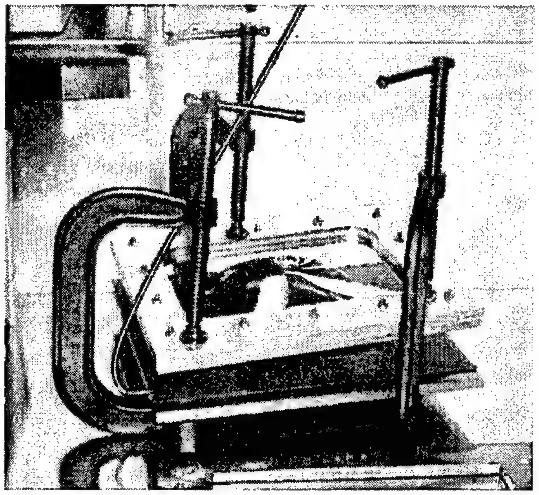


Figure 30. Setup used to determine feasibility of thermoforming a plastic substrate.

Initially a clay mold was used. However, in addition to the non-uniformity, it was found that the plastic substrate adhered to the mold during the thermoforming process. This makes this mold material not viable for the experiments. Consequently, it was necessary to fabricate a metallic mold. However, metal molds are extremely expensive and time consuming to fabricate. AMI has determined that a machinable epoxy made from polymeric resin with suspended aluminum particulates can be used for molds. The hardened resin can be machined and can withstand temperatures in excess of 150°C. The epoxy was cast using existing visors and machined to the HGU-55/P shape. Figure 31 shows the mold fabricated.

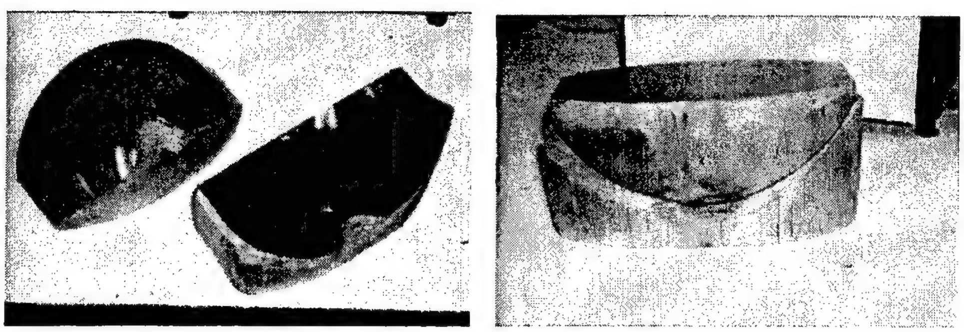


Figure 31. Epoxy molds for thermoforming (a) mold halves (b) assembled.

AMI plans to continue its effort in this area by considering other conductive coating materials which can be printed after the thermoforming procedure. This will allow AMI to develop ruggedizable visors without the multiple reflections and parallax.

4. Facility and staff

AMI has been working on this project for the past three years. During this time, it has built its resources, both in personnel and equipment, towards the successful realization of its goals.

4.1. Personnel

AMI has 14 employees. Five hold Ph.D. degrees in Physics, Chemistry and Polymer Science. During the past year, Mr. E.Y. Park, from Samsung Electronics, joined AMI as chief manufacturing engineer. Mr. Park has over 15 years of experience in LC display manufacturing; and he is leading the manufacturing process development.

Dr. Bahman Taheri, CEO and CTO, is one of the three founders of the company. He is a physicist and Adjunct Assistant Professor of Chemical Physics, Kent State University.

Dr. Peter Palffy-Muhoray, CSO, is one of the three founders of the company. He is a physicist, Professor of Chemical Physics and the Associate Director of the Liquid Crystal Institute at Kent State University.

Dr. Tamas Kosa, COO, is one of the three founders of the company. He is a physicist, and Adjunct Assistant Professor of Chemical Physics at Kent State University.

Mr. Volodymyr Bodnar, Project Manager. With a background in optics and physics, in which he holds the B.Sc. degree, he has been working in the area of electro-optics of liquid crystals for the past 5 years. He is responsible for development and characterization of the high order parameter dye – liquid crystal mixtures.

Dr. Yoan Kim, Polymer Scientist: He received his training in polymer science at the University of Akron. He has been working on this project for 4 years. He is responsible for the successful development of flexible substrates for eyewear. He currently leads the plastics development effort.

Dr. Ludmila Sukhomlinova, Senior Chemist: Renowned for her expertise in liquid crystal synthesis, she heads the materials synthesis effort at AMI. She has designed and synthesized the high order parameter dyes required in AMI's liquid crystal eyewear. She is responsible for the production of dyes and other mixture components.

Mr. E.Y. Park, Senior Manufacturing Engineer: He recently left his position as senior manufacturing engineer with Samsung Electronics to join AMI. He has over 15 years experience in LC device manufacturing. He leads the manufacturing process development program.

Dr. LinLi Su, Electro-optics physicist: She received her Ph.D. in liquid crystal and joined the company in January of 2003.

Mr. Roy Miller, Display Engineer: He has been working on LC processing for the past 4 years. He holds a B.Sc. degree in physics. He is involved in prototyping and fabrication of plastic cells.

Ms. Christine Woodby, Display Engineer: She has recently joined AMI to assist in reduction to manufacturing phase of the project.

Other staff members include a display engineer, a display technician, a machinist, a chemical technician, an accountant and a secretary.

4.2. Laboratories

During this period AMI has setup a facility to allow it achieve the goals and tasks of the proposed plans. In addition to the SBIR, AMI has been able to leverage several contracts from the private sector and has used this to increase its facility. Currently AMI has prototyping, characterization and synthetic facilities which allow it to perform all work in-house.

Synthesis: An organic chemistry laboratory is available for the synthesis of high performance dyes and other specialized mixture components designed for eyewear performance and not commercially available.
Characterization: Full facilities are available for electro-optical characterization of materials, components and devices to US Air Force standards. Capabilities include measurement of the transmission, absorption, haze, response time, and spectral response. A QUV tester is available for environmental testing.

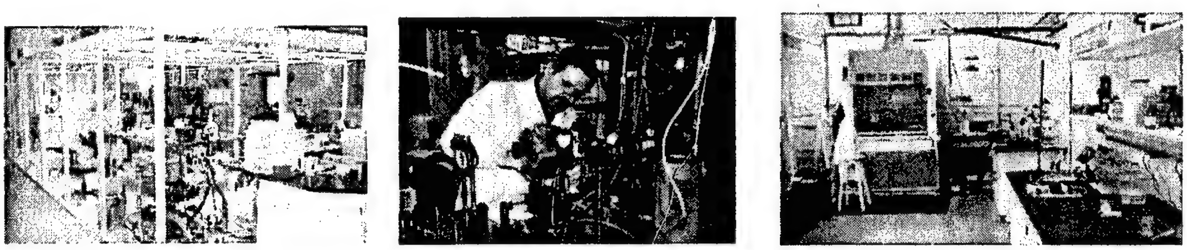


Figure 32. AMI's cleanroom, characterization and synthetic facility

Prototyping: A 300 sq.ft. class 100 cleanroom equipped with cleaning, spin coating, lithography, cell assembly, filling and sealing equipment is available for prototyping.

Polymer processing: Processing equipment, ranging from thermoforming and ultrasonic welding to cutting, shaping and laminating is available for development and fabrication.

Machine Shop: Equipment, including a computer controlled milling machine, lathe and welder allows fabrication of specialized equipment as well as molds required for prototype fabrication.

5. Commercialization efforts

AlphaMicron's VALiD technology offers a haze free light control mechanism capable of being implemented on curved plastic substrates. This system has a number of applications in varying fields. In the area of eyewear, it can be viewed as having applications in both private and military sectors. Military applications include goggles for ground troops and visors for avionic applications. Consumer markets include sports, as well as prescription eyewear. Figure 33 shows the range of the applications for VALiD for eyewear. AMI is interested in commercializing in different areas and thus use the combined leverage power to be able to meet the cost requirements for each sector.

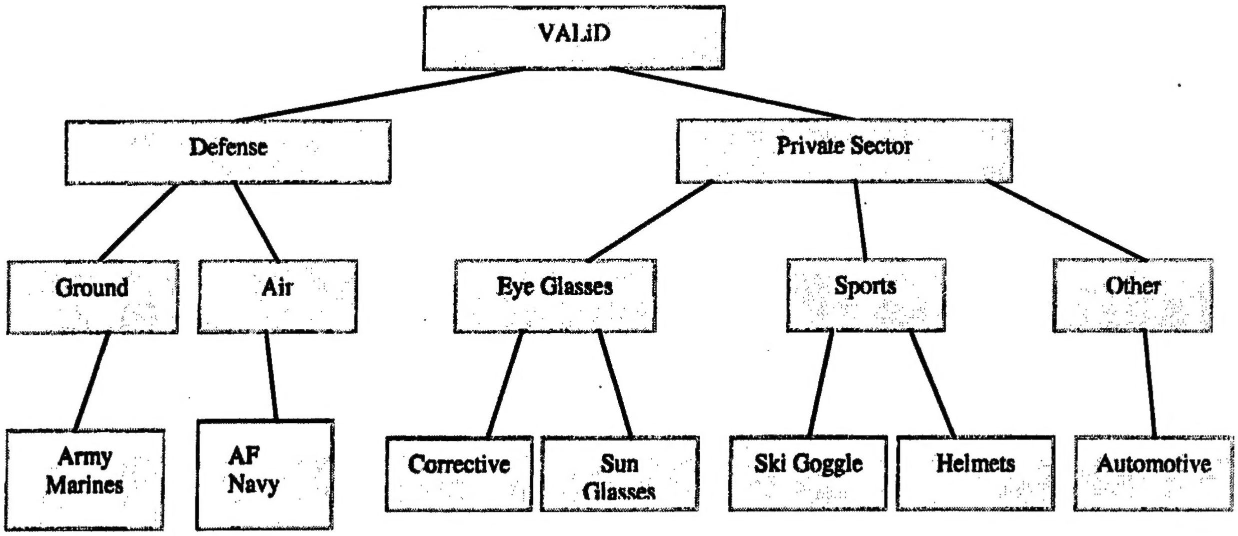


Figure 33. Application of VALiD eyewear in consumer and military markets

The military application is the focus of the funded research. They will include both cylindrical goggles for ground troops as well as visors for avionics. Figure 34 shows the potential products in these markets.

Figure 34. Potential products for Army and Air Force.

For the Air Force applications, AMI's liquid crystal eyewear can be used either as a stand-alone system, or it can be integrated into combined systems using technologies such as helmet-mounted displays (HMDs). Currently, no competing technologies exist which can meet US Air Force requirements for VTVs. Since liquid crystal visors have not been available until now, the number of units needed is not yet known. However, VSI (the primary contractor for the US Air Force and Navy's Joint Helmet Mounted Cueing System) has estimated that the US Air Force alone may require 20,000 visors per year with unit costs estimated to be in the thousands of dollars. There are more than 500,000 Army personnel that can use the liquid crystal SWD Army goggles.

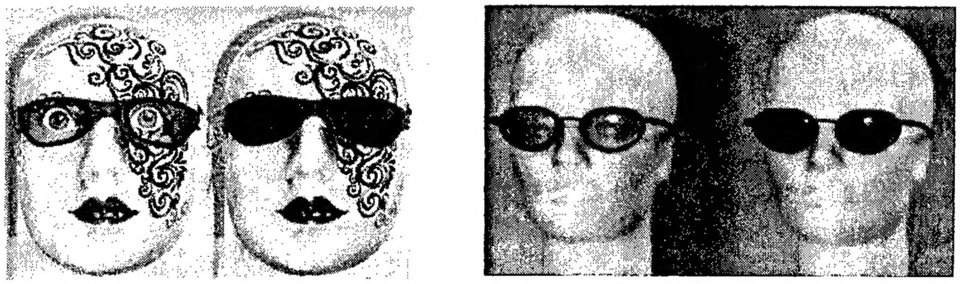


Figure 35. Consumer market eyewear applications

The commercial eyewear industry today supplies two distinct groups: the plano and the ophthalmic markets. The plano market consists of ski goggles, motorcycle helmet visors, as well as non-prescription sunglasses. The combined US market for these products is in excess of $4 billion/yr. Ophthalmic eyewear is approximately a $30 billion/yr US industry. This includes clear prescription lenses, prescription sunglasses and transition eyewear using photochromic materials. The total eyewear market worldwide is approximately $60 billion/yr.

A recent study indicates a strong consumer desire for variable transmittance eyewear. AMI believes it can establish a dominant position in all of the above markets with its revolutionary liquid crystal eyewear technology. The current mixtures are well suited for sun-sport applications including prescription sunglasses. AMI further expects that it will be able to penetrate the reading glasses market with its next generation mixtures.

At the end of this project, AMI established links to the optical industry for both military and consumer market applications. It is expected that the developments made during this funding will result in strategic alliances between AMI and manufacturers and distributors of eyewear products. Possible candidates for the consumer market include lens manufacturers SOLA and Essilor and distributors such as Luxottica, Oakley, Smith, Bolle, and Maui Jim's. AMI has worked with visor manufacturers, including Gentex and Aotec, for development of visors for DoD applications.

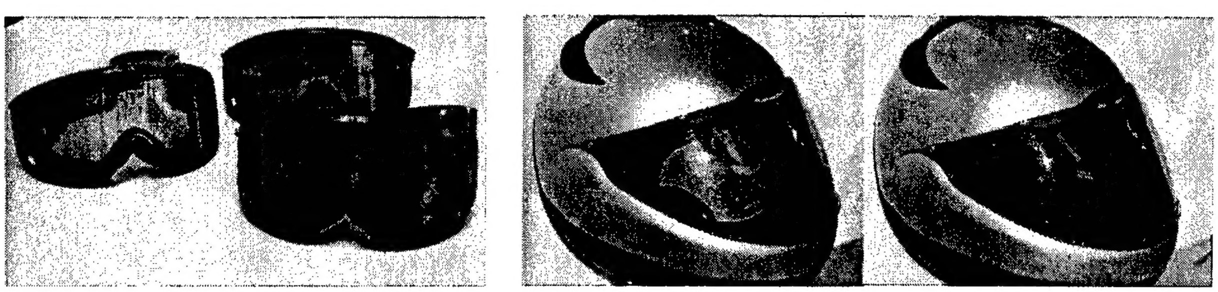


Figure 36. Use of AMI's VALiD for sport eyewear (a) ski goggles (b) motorcycle visors.

For long-term viability of liquid crystal eyewear as a consumer product, AMI must identify strategic partners in liquid crystal and optical communities. Given AMI's current resources and its extensive knowledge of liquid crystal science and technology, the latter is more paramount.

During the past four years, AMI has had a number of interactions with companies in the optical industry. These interactions were greatly expanded after AMI attended the VisionExpo East in New York on March 15-18th 2002 where it debuted its liquid crystal eyewear. The show is a forum for optical companies interested in presenting their fall fashions. The attendees included lens manufacturers, eyewear distributors and retailers.

AMI is continuing to review and study the key companies in the optical industry and their distribution channels. It is considering companies which focus on:

(1) lens fabrication (SOLA, Essilor);
(2) branding and distribution of goggles (Oakley, Smith, Bolle);
(3) branding and distribution of sunglasses (Oakley, Ray Ban, Maui Jim's);
(4) direct sales (Polo, BMW, Armani).

A potential partner in each category will be selected based on company's level of interest and commitment to the project as well as the capability for a successful launch. The goggles and sunglasses manufactured will be distributed to the potential partners for marketing study in accordance with the consumer eyewear market timelines. Furthermore, the potential partners will perform durability test to confirm the results obtained on liquid crystal lenses by AMI. These tests will be documented to demonstrate compliance with consumer eyewear industry requirements.

AMI will continue to identify potential partners in the liquid crystal manufacturing community. The criteria for this selection will be based on the manufacturers level of interest and capability. AMI expects that it will transfer its know-how of plastic fabrication to the company to assist in mass-production of the eyewear.

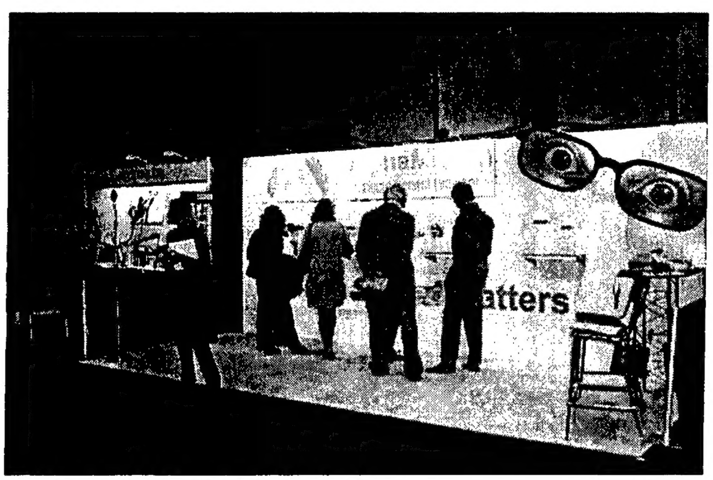


Figure 37. AMI debuting its technology at the Vision Expo East in 2002

6. Awards and Recognitions

In the five years since its inception, AMI has become the recognized leader in the implementation of liquid crystal technologies on curved plastic substrates. It has received a number of recognitions and awards during the past year. It was the recipient of the 2001 *Technology Client of the year award from National Business Incubator Association (NBIA)* and recently it was awarded a *Thomas Edison Emerging Technology Award* by the Ohio Department of Development. The State of Ohio has recognized and awarded AMI for its achievements; and it was visited by US congressman Tom Sawyer. The VALiD technology has been featured in Lockheed-Martin's Center for Excellence, the Navy League show, US Air Force briefings, several NSF's ALCOM center articles, National Public Radio and a number of newspaper articles and the Feb 2003 issue of Information Display, published by the Society for Information Display. A detailed list is available at http://alphamicron.com/awards&honors. AMI is a member of "e-corridor" of Ohio.

AMI is an active contributor to local and State development initiatives, and plans to maintain all of its operations in Ohio. It is anticipated that commercialization of AMI's innovative eyewear technology will contribute to the economic development of the State through providing jobs for skilled workers, income to the State through taxes, and through establishing the reputation of Ohio as home to successful technology based industry. AMI's eyewear technology is ideally suited for the optical corridor which is being established for the consumer optical industry in Ohio.